Prompt Cusps, Stellar Encounters & The Dark Matter Annihilation Signal

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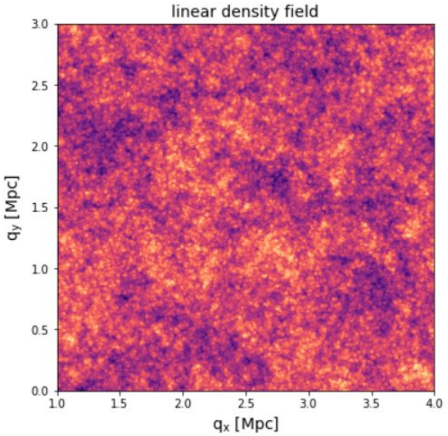
DM2023, Santander, May 31, 2023

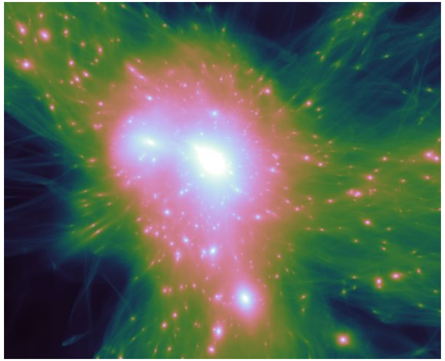
with Go Ogiya, Simon White & Raul Angulo

NFW Haloes vs Prompt Cusps

Mpc
scales



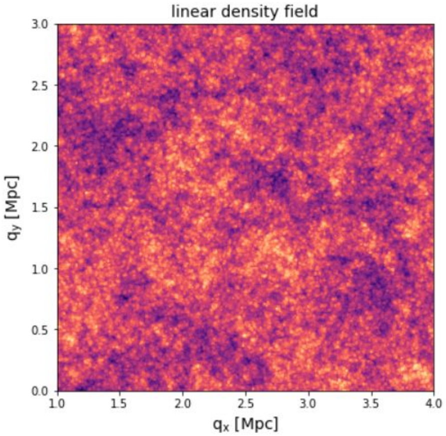
collapse



NFW
Halo

NFW Haloes vs Prompt Cusps

Mpc
scales



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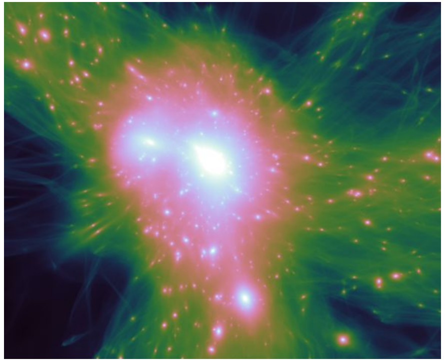
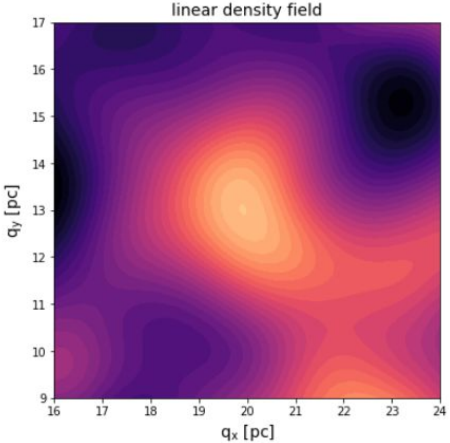


NFW
Halo

pc
scales



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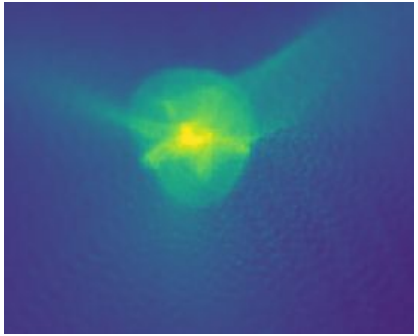
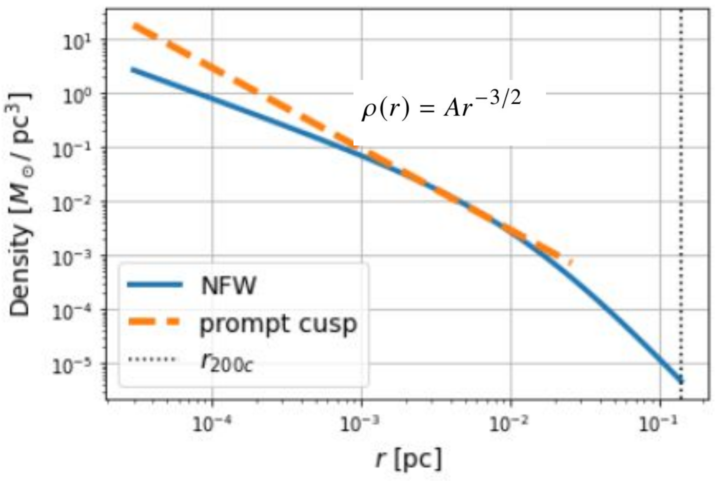


Delos & White (2022)

prompt
Cusp

~ Mearth

Prompt Cusps



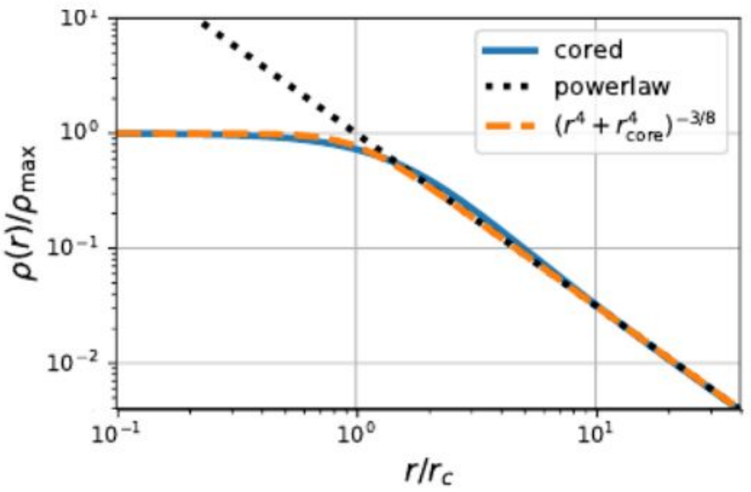
Diemand et al. (2005), Ishiyama et al. (2010), Angulo et al. (2017), Ogiya & Hahn (2018), Delos et al. (2018), Delos & White (2022), White (2022)...

- WIMP density field smooth on ~ parsec scales
- Peaks of the density field collapse into dense small objects called **"prompt cusps"**
- These are much **denser** than **NFW profiles**

➢ Drastically modifies predictions for **self-annihilation radiation**

$$J = \int \rho^2 d^3 r$$

Prompt Cusps & DM self-annihilation signal



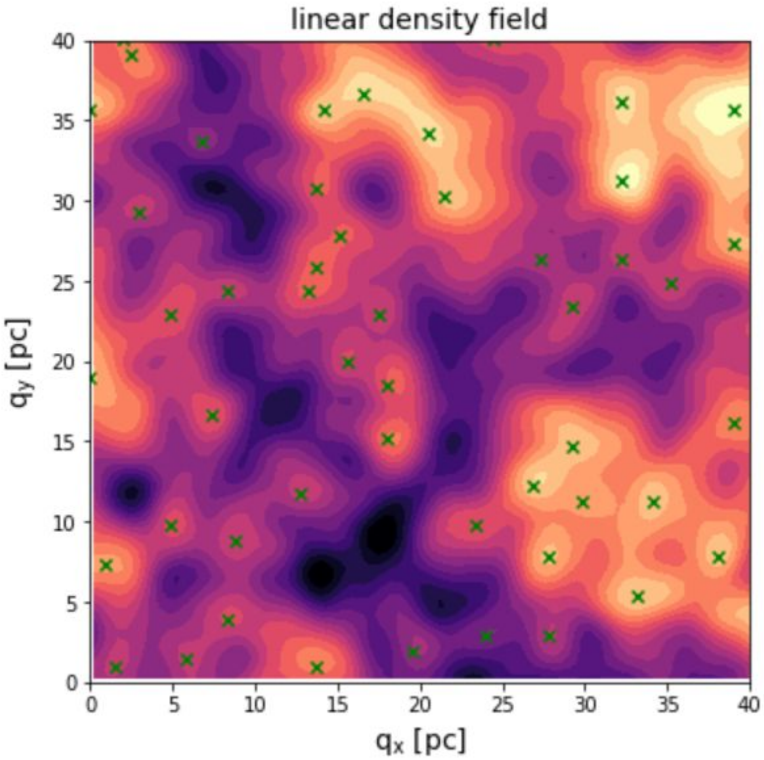
- For a -3/2 power-law profile the annihilation rate is centrally divergent

$$J = \int_{r_1}^{r_2} \rho^2 d^3 r \propto \log(r_2/r_1)$$

- The power-law profile extends up to a **core radius** set by the primordial phase space density constraint

M ~ Mearth, rcusp ~ 1000 AU, rcore ~ 2 AU

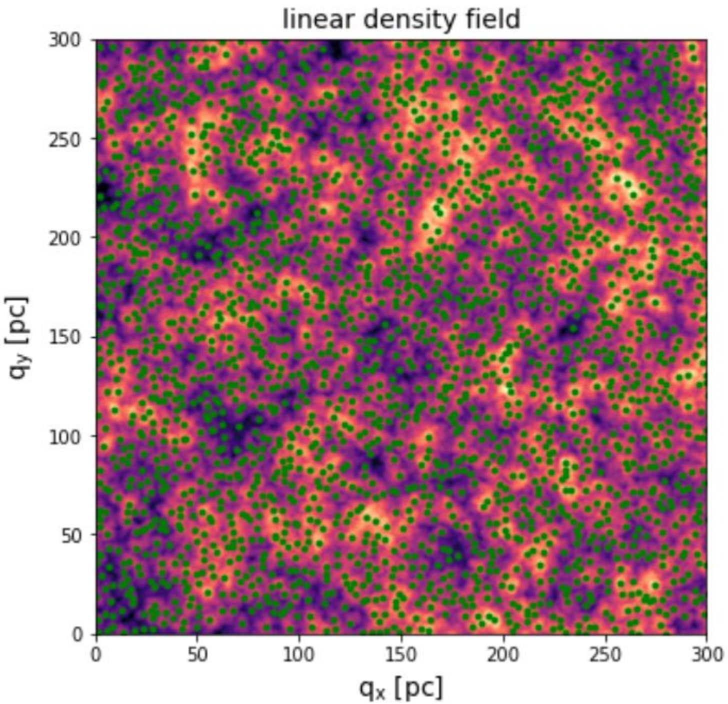
Prompt Cusps & DM self-annihilation signal



Delos & White (2022) calculation:

- Each peak of the initial density field forms a prompt cusp
- Peaks are approximately uniformly distributed in Lagrangian space

Prompt Cusps & DM self-annihilation signal



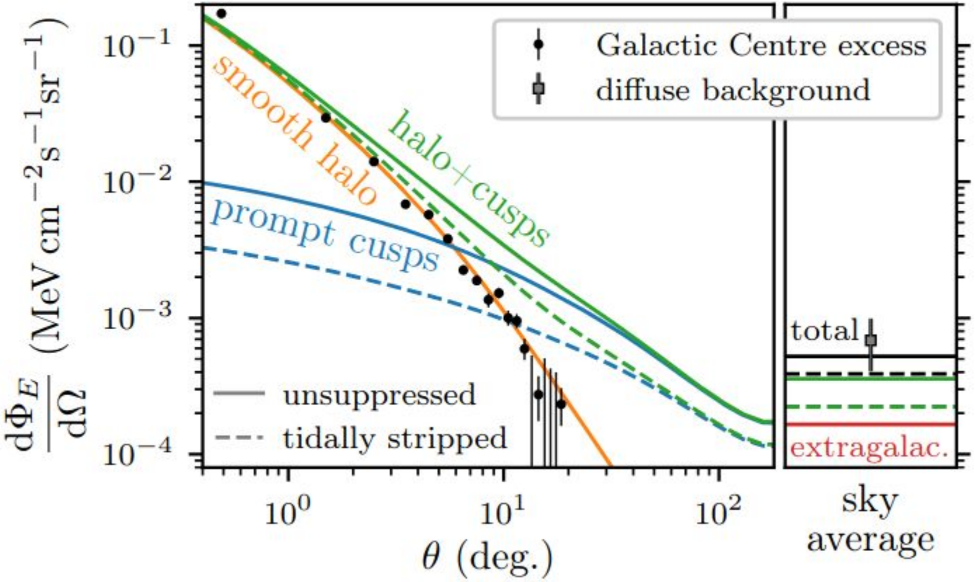
Delos & White (2022) calculation:

- Each peak of the initial density field forms a prompt cusp
- Peaks are approximately uniformly distributed in Lagrangian space

- If cusps are not disrupted then
  - ➢ Each solar mass of DM contains ~ 10^4 cusps
  - ➢ Cusps follows the DM distribution
  - ➢ ~ 10^{16} cusps with M ~ Mearth in Milky Way
  - ➢ **Boost factor** of **10^2** - **10^4**

Dramatic implications for annihilation predictions!

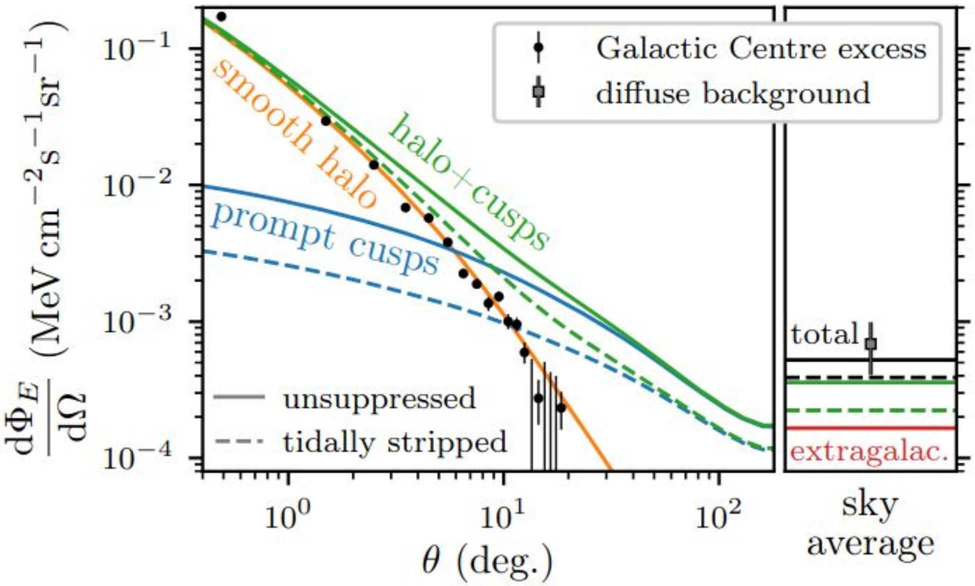
Prompt Cusps & The Fermi-LAT Galactic Centre Excess



Delos & White (2022)

$$J = \int \rho^2 d^3 r$$

Prompt Cusps & The Fermi-LAT Galactic Centre Excess



Delos & White (2022)

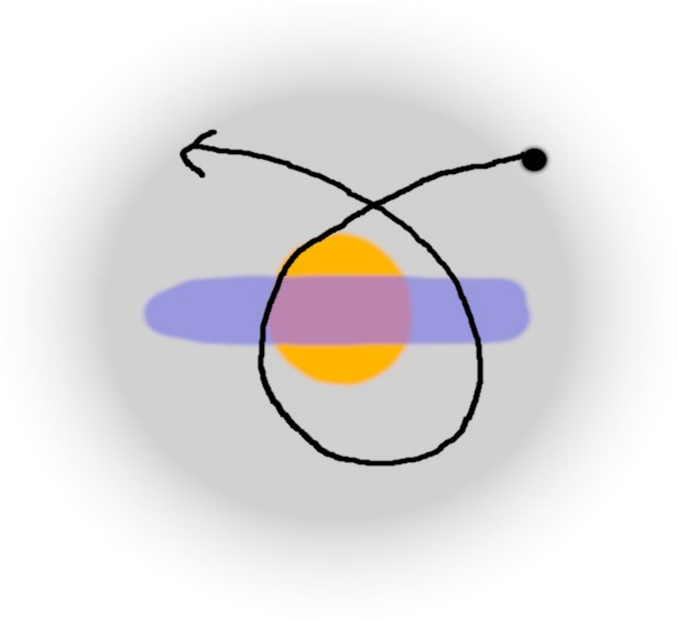
$$J = \int \rho^2 d^3 r$$

This estimate neglects **stellar encounters**.

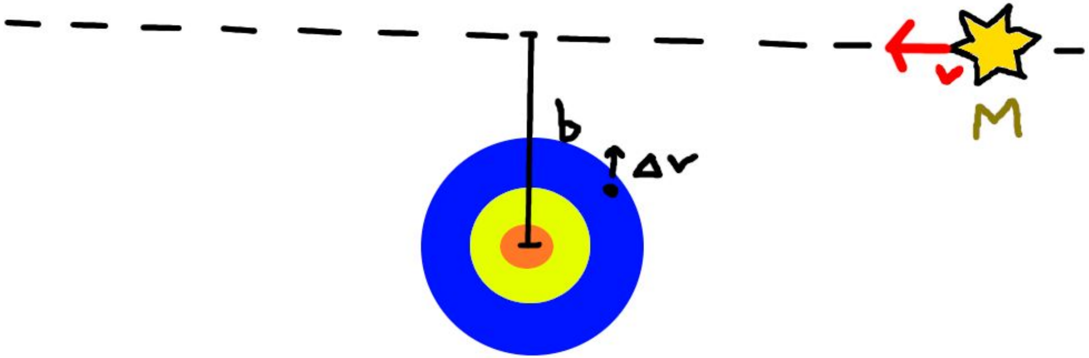
10° ~ 1kpc is deep in the baryonic components of the Milky Way

Prompt Cusps & Stellar Encounters

- Do stellar encounters affect the GCE prediction?



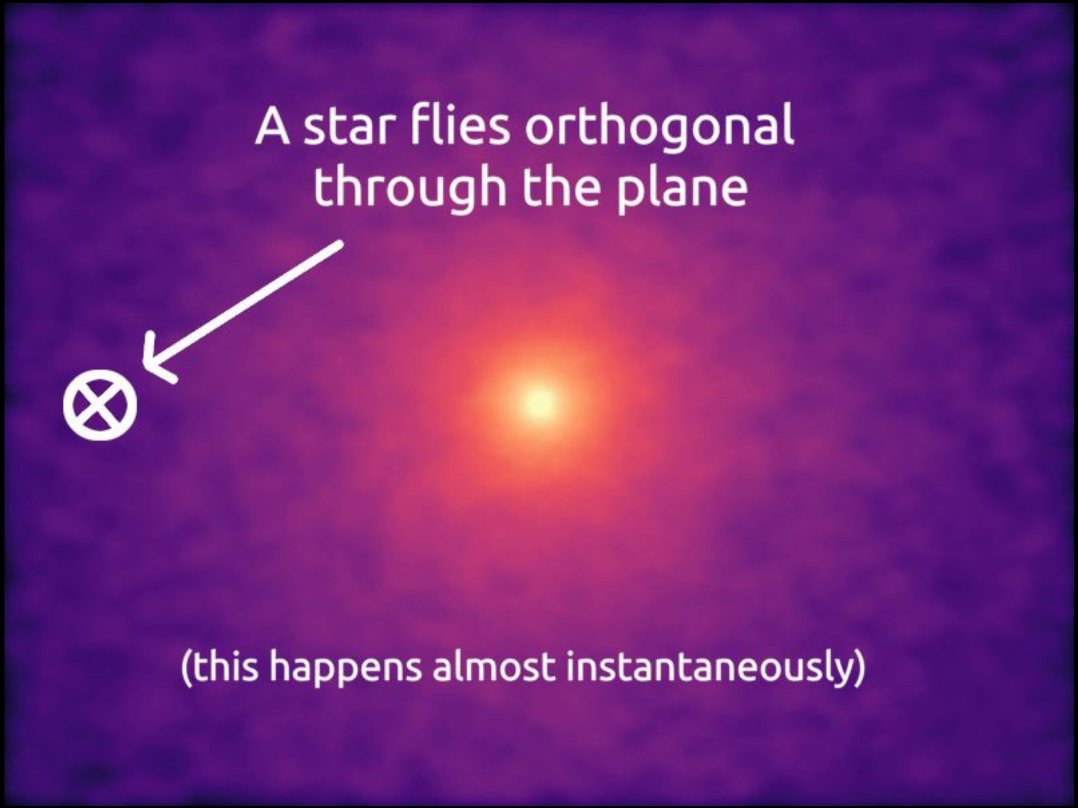
The shock parameter B

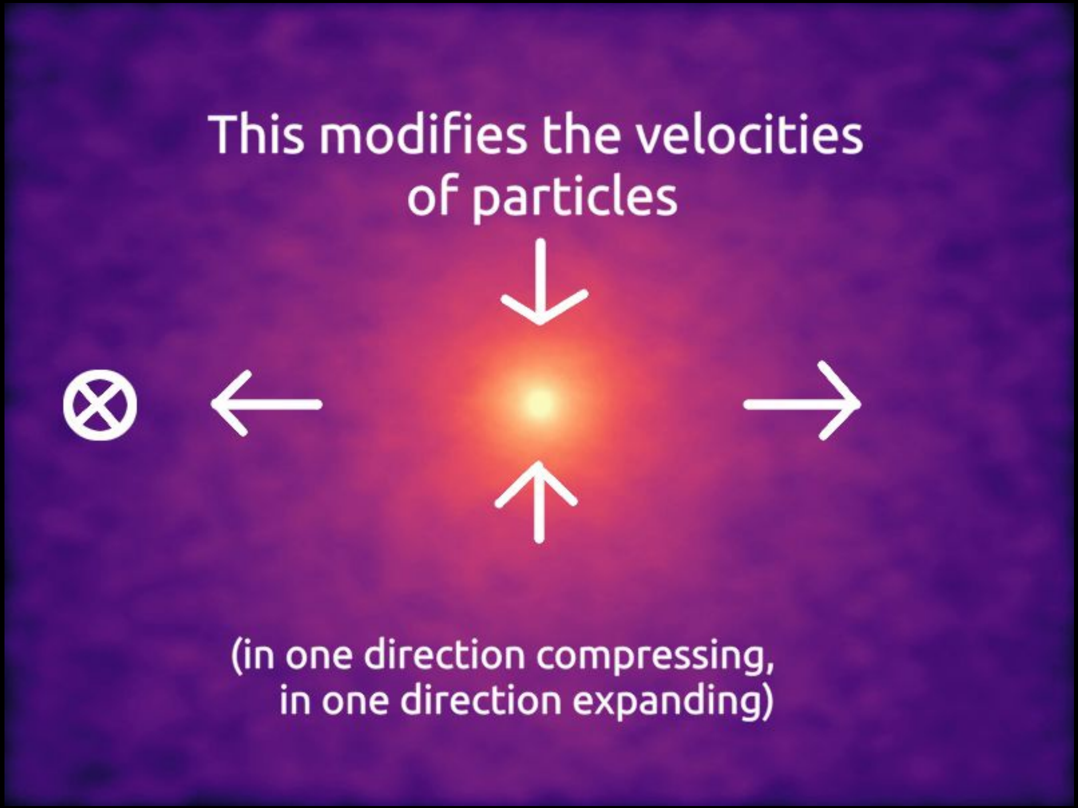


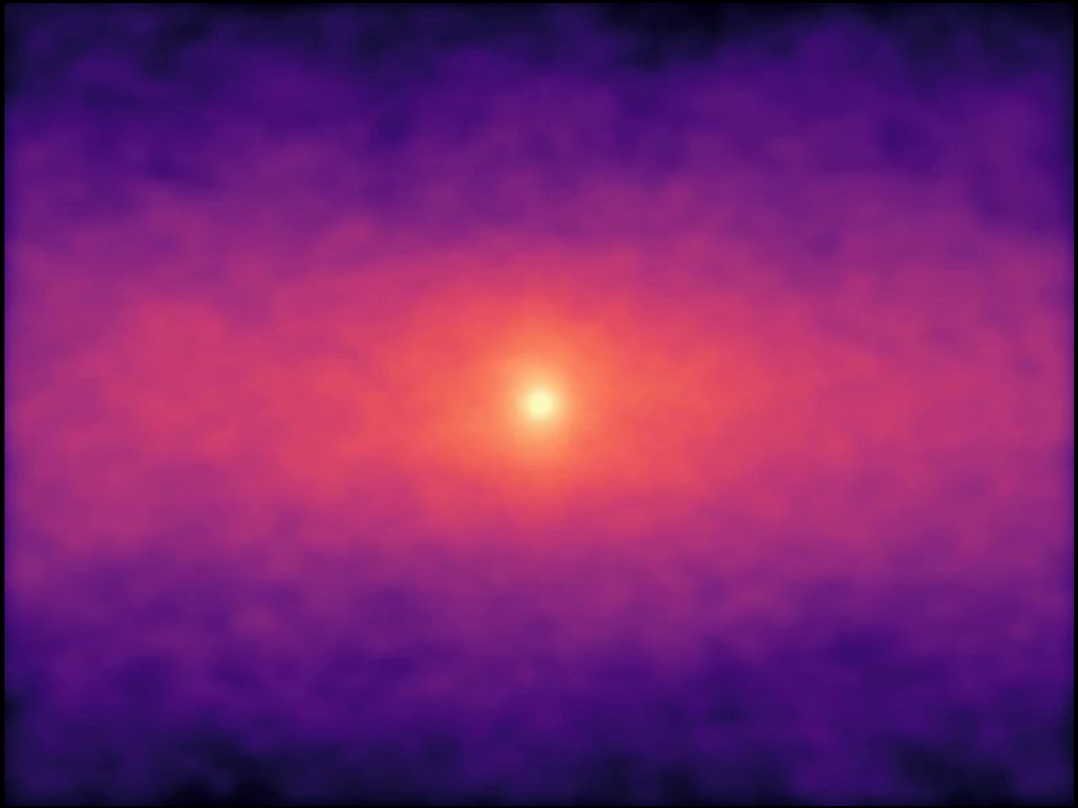
$$\Delta v = B \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix} \Delta x$$

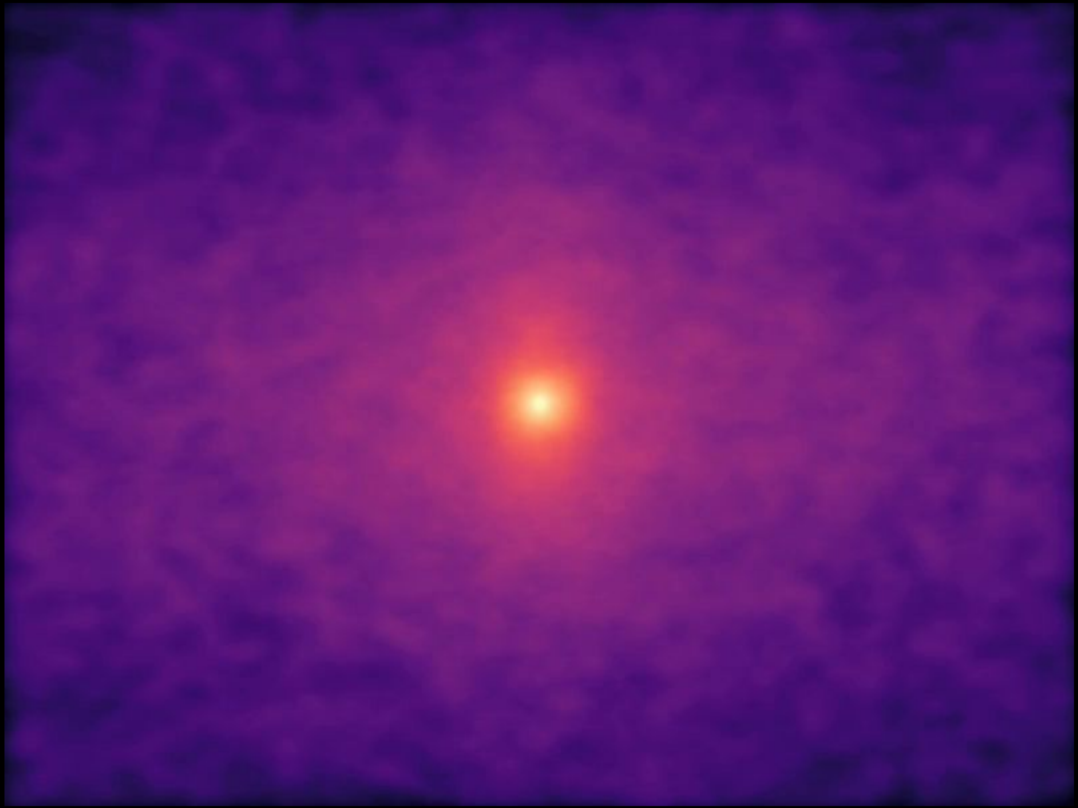
$$B = \frac{2GM}{vb^2}$$

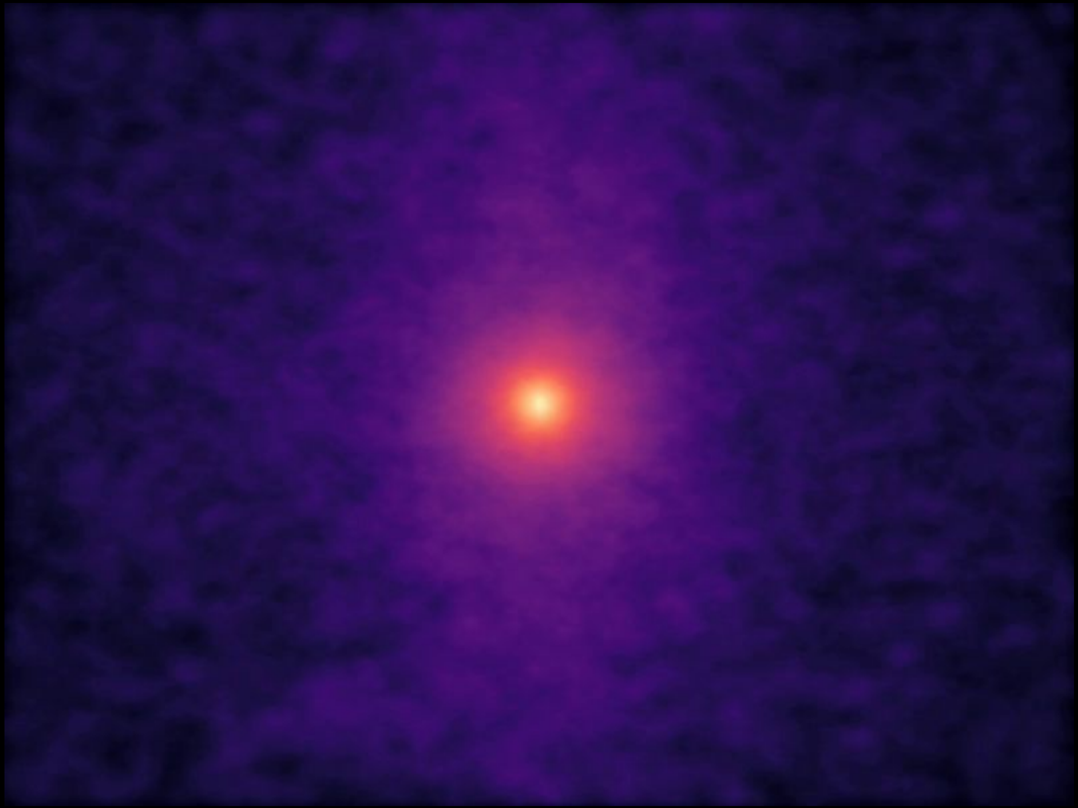
B : Shock parameter
M : stellar mass
b : impact parameter
v : impact velocity

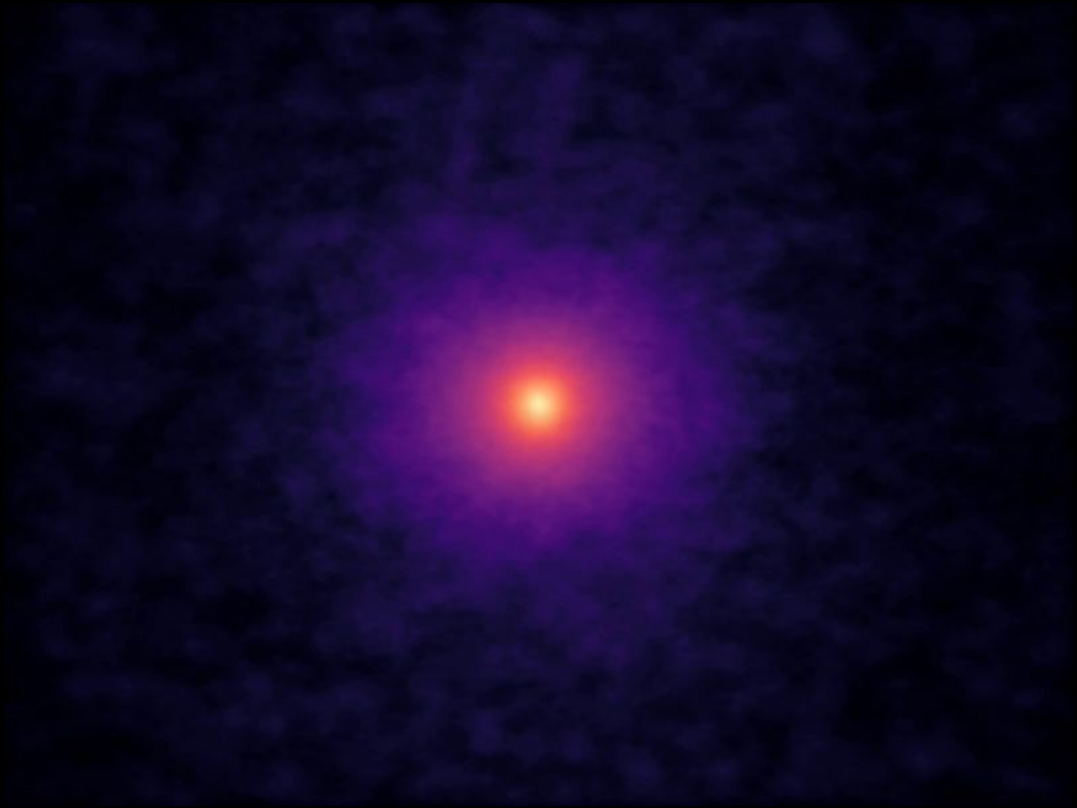

A star flies orthogonal
through the plane
(this happens almost instantaneously)

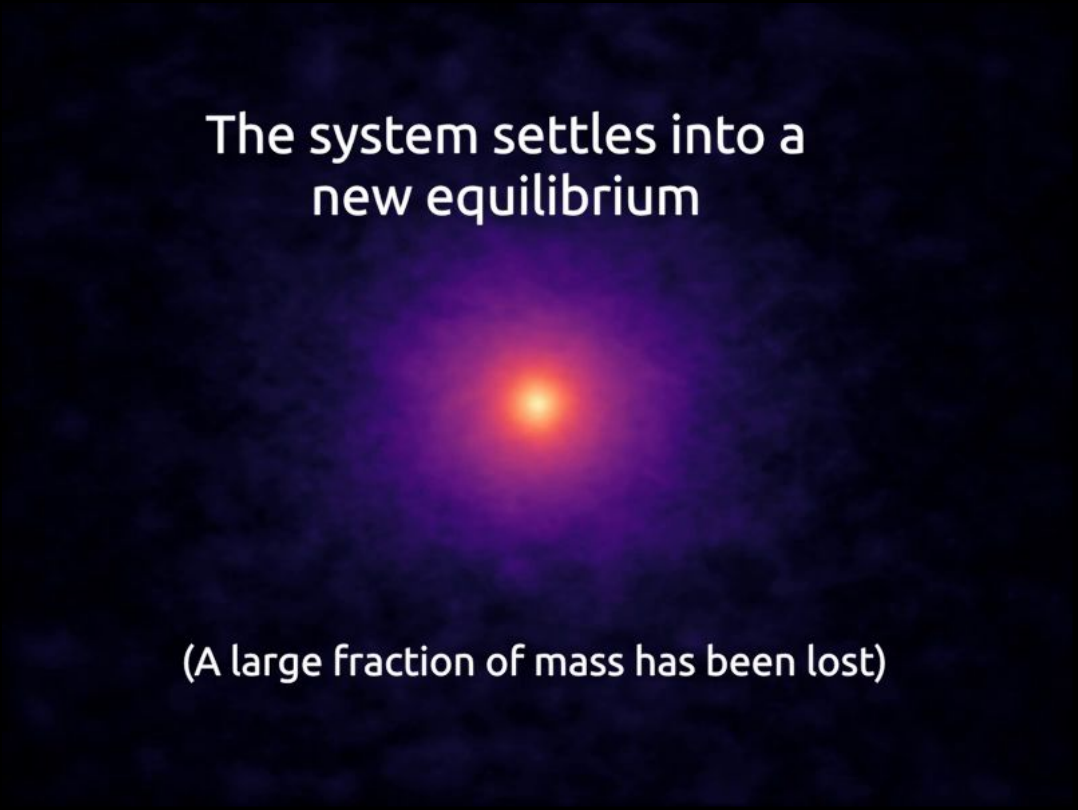

This modifies the velocities
of particles
(in one direction compressing,
in one direction expanding)



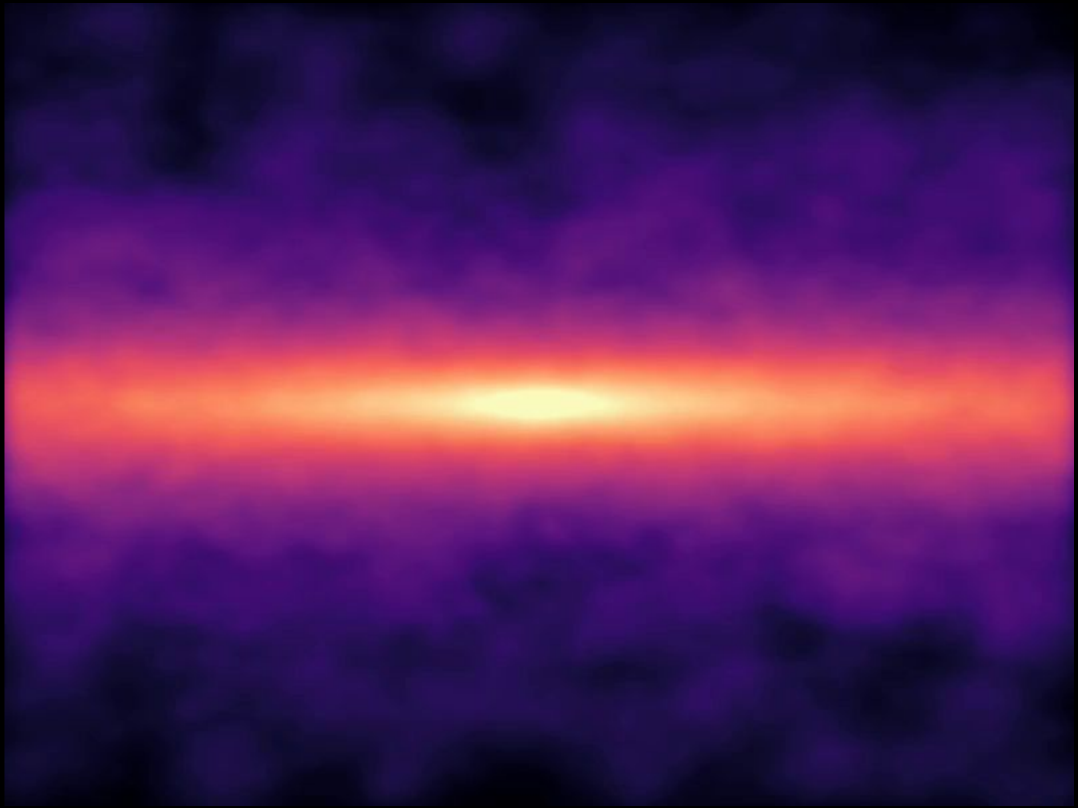


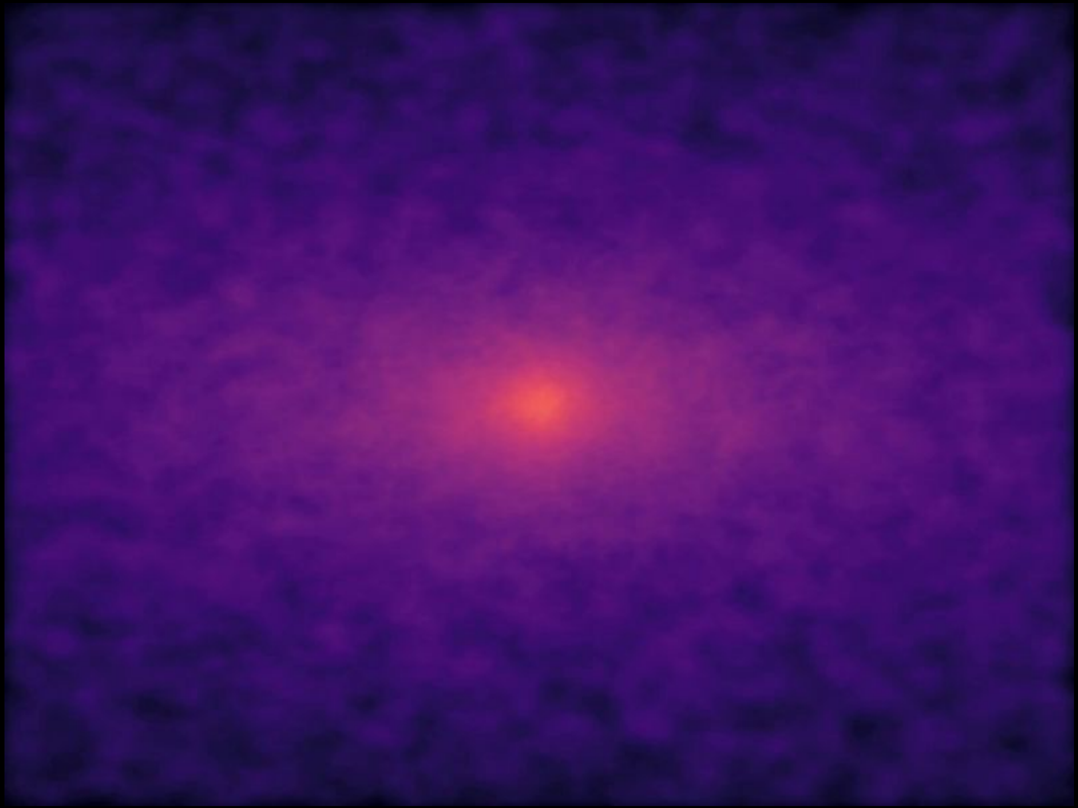





The system settles into a new equilibrium
(A large fraction of mass has been lost)


This time we consider a
closer encounter
(creating a stronger shock)

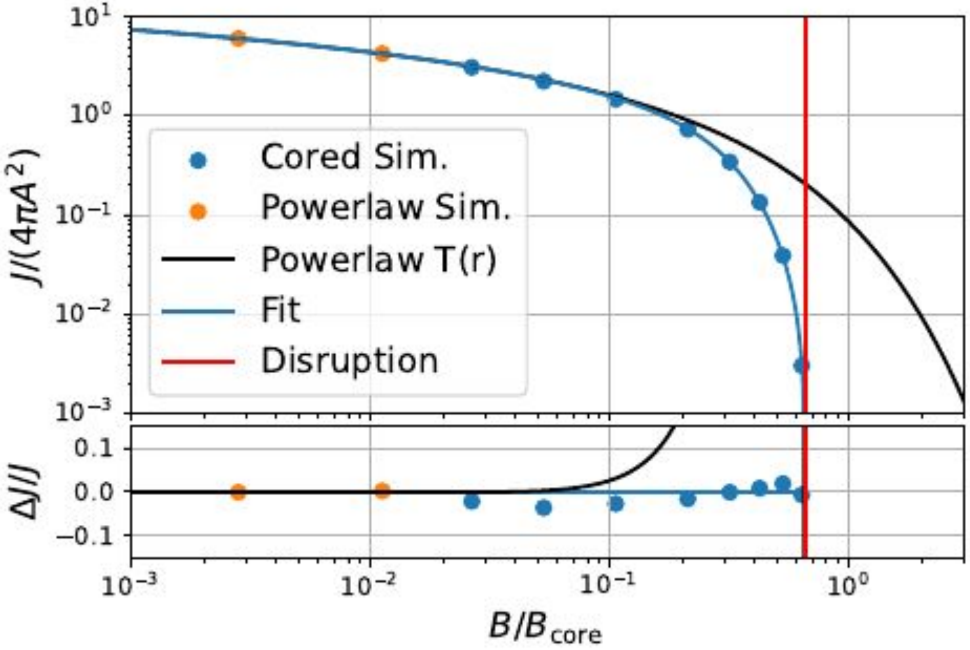




For strong enough shocks the system disrupts completely

(For this it is relevant, that the initial profile has a finite phase space core)

Encounters & Cored Powerlaw Profiles



$$B_{\mathrm{core}} = \frac{v_{\mathrm{circ}}(r_{\mathrm{core}})}{r_{\mathrm{core}}}$$

The “stellar encounter conspiracy”

$$B = \frac{2GM}{vb^2}$$

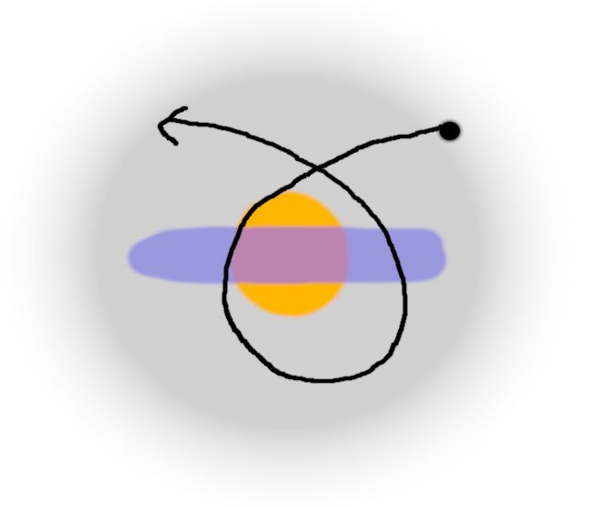
The **distribution of shocks** is a Poisson distribution with expectation number

$$N(>B) = \frac{B_*}{B}$$

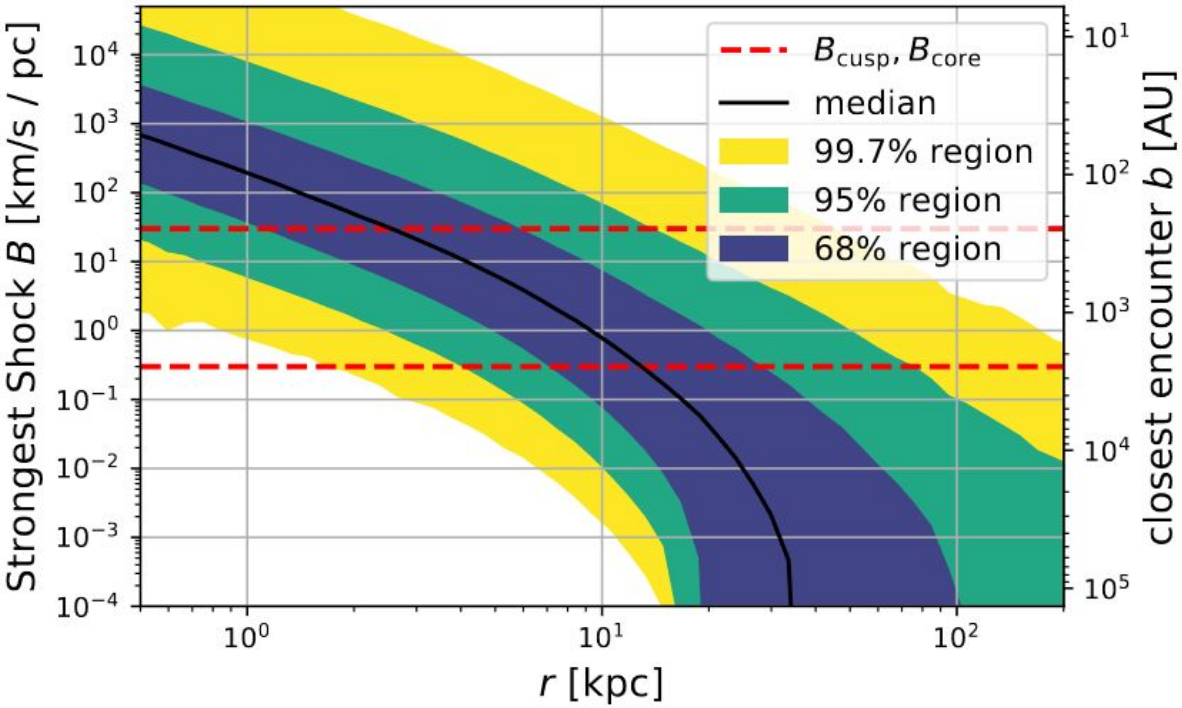
Which depends only on the **integrated stellar mass density**:

$$B_* = 2\pi G \int \rho_*(\vec{x}(t))dt$$

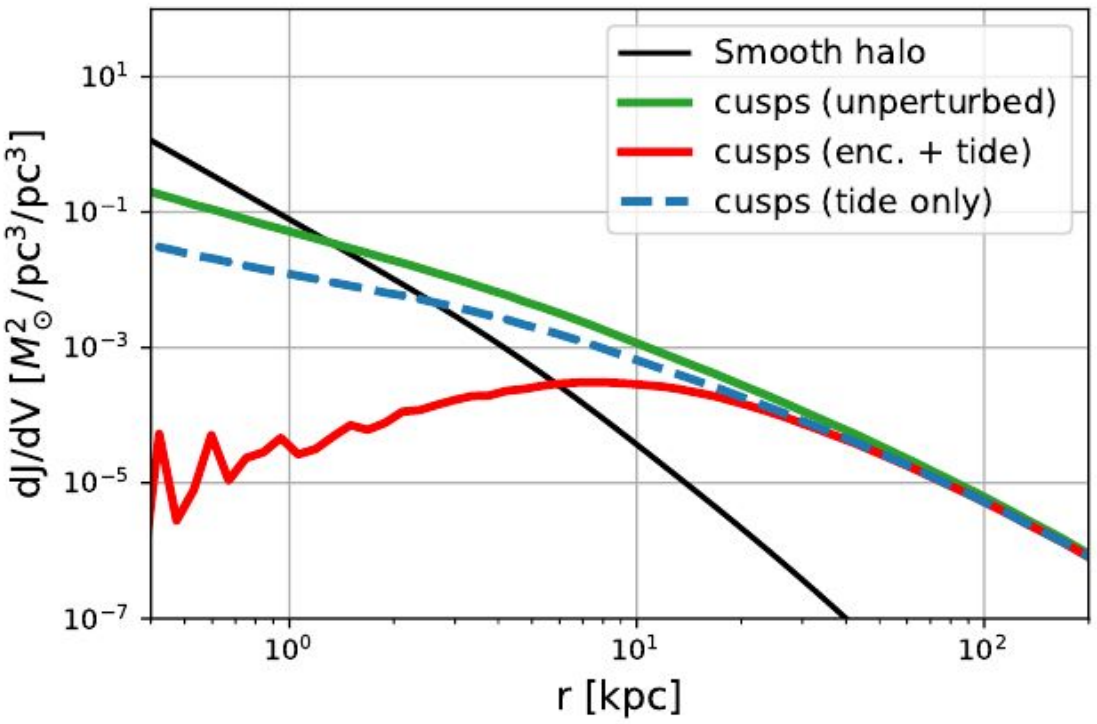
It **does not depend** explicitly on the stellar **phase space distribution**, stellar **mass function** nor **orbital parameters**



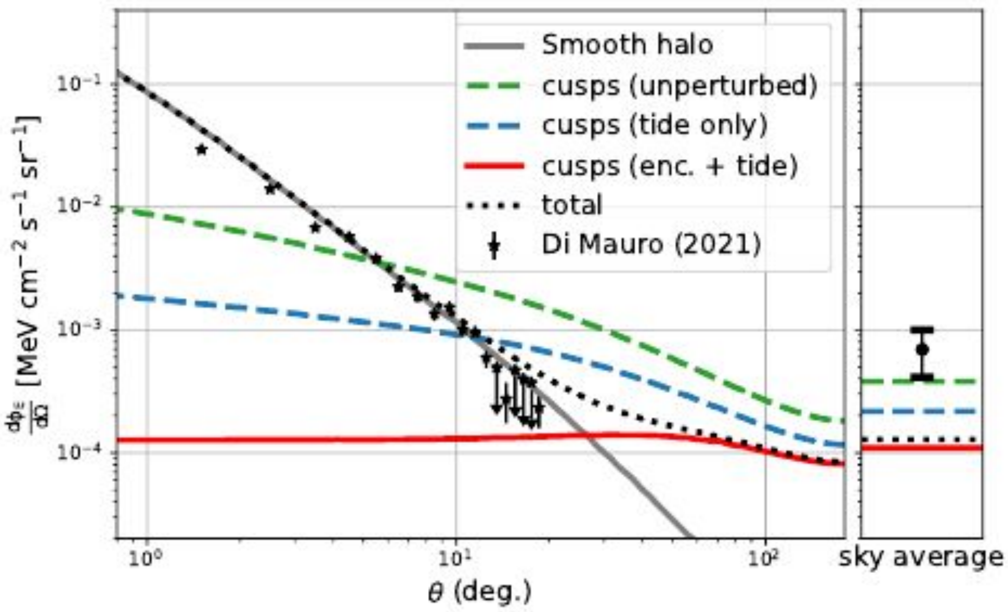
Encounter Distribution



Results: The reduction in Luminosity in the Milky Way

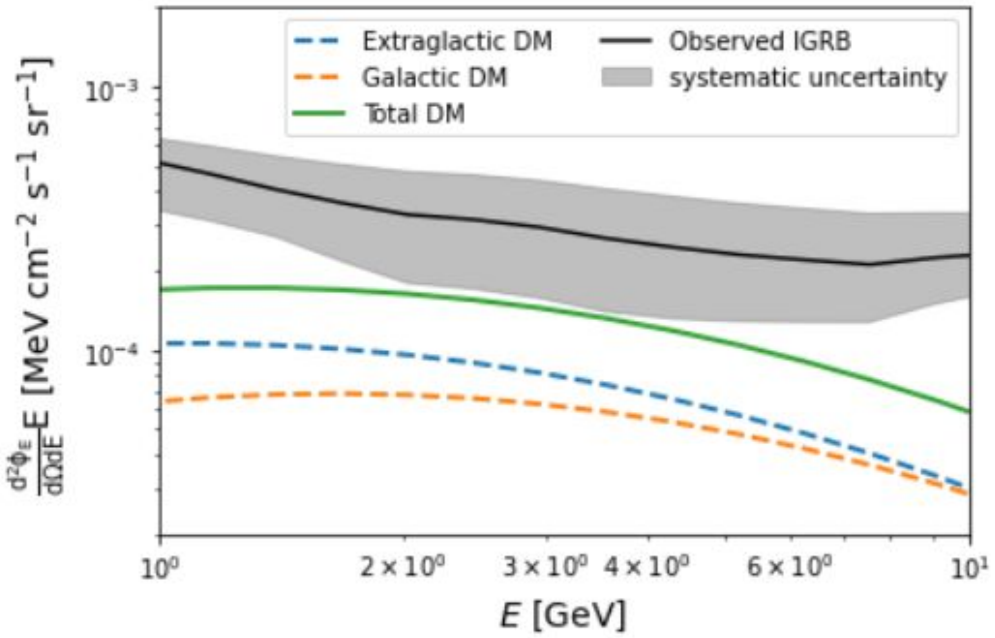


The effect of encounters on the GCE



After accounting for stellar encounters prompt cusps do not contribute to the GCE

Cusps & the Isotropic Gamma Ray Background (IGRB)



observed IGRB from Fermi-LAT
(Ackermann et al, 2015))

The IGRB should still include a strong signal from prompt prompt cusps, even after accounting for stellar encounters
(between **20%-80%** when considering different WIMP models)

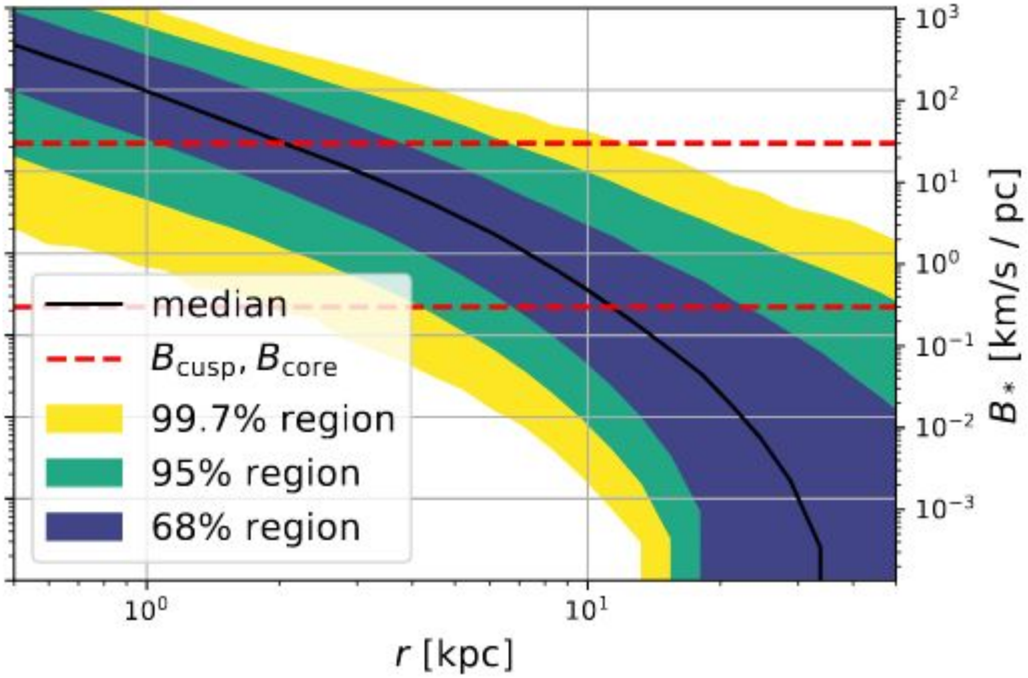
Conclusion

- If DM is a WIMP ~ 10^{16} **prompt cusps** (M ~ Mearth) are orbiting in the Milky Way and significantly enhance DM self-annihilation predictions
- **Stellar encounters** disrupt the majority of cusps in the vicinity of the disk r < 20kpc
- After accounting for this effect, there is **no Tension** between the **Galactic Centre Excess** and DM predictions
- If the GCE is due to **dark matter**, then we additionally expect that **20%-80%** of the **Isotropic Gamma-Ray Background** is due to DM annihilation
    - If such a signal would be found, strong backup for DM interpretation of GCE
    - If there is no room for such a signal, we can likely exclude that the GCE is due to DM

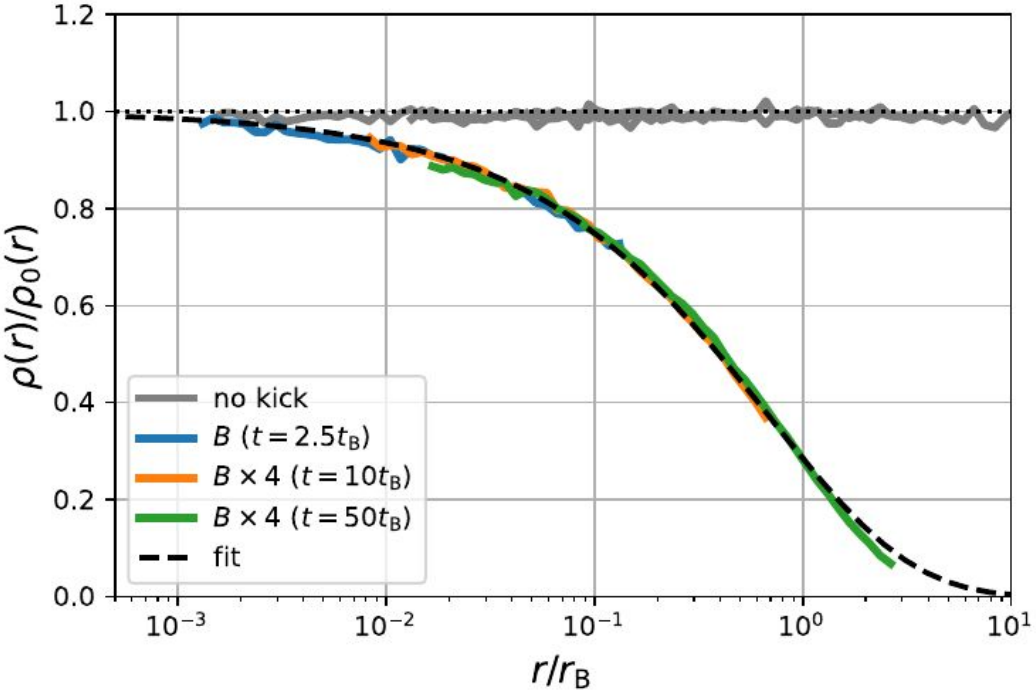
Stücker, Ogiya, White & Angulo (2023)

Appendix

Stellar encounters in the Milky Way



Encounters & Pure Powerlaw Profiles



$$r_B = \left(\frac{8\pi G A}{3B^2}\right)^{2/3}$$

$$T(r) = \exp(-\alpha(r/r_B)^\beta)$$

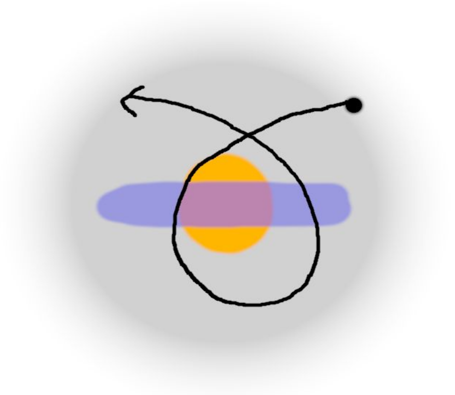
The “stellar encounter conspiracy”

$$B = \frac{2GM}{vb^2}$$

The distribution of shocks depends only on the integrated stellar mass density:

$$B_* = 2\pi G \int \rho_*(\vec{x}(t)dt)$$

It does not depend explicitly on the phase space distribution, stellar mass functi
orbital parameters

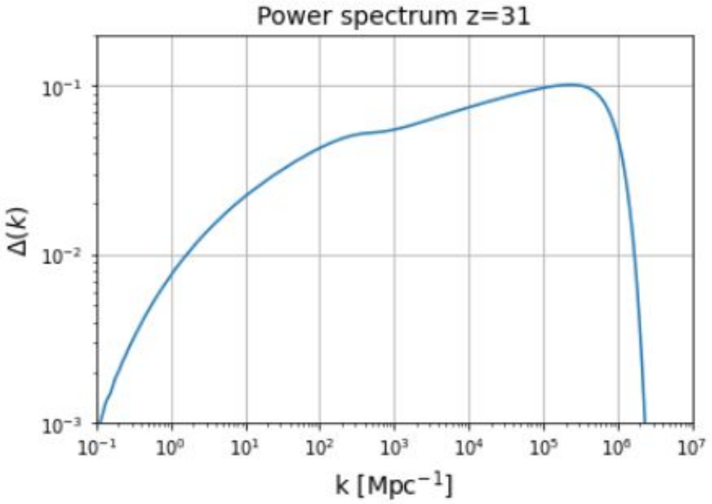


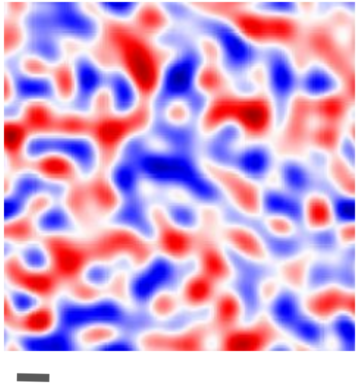
The probability of having exactly k encounters with shock parameter > B is a Poisson distribution with expectation value

$$N(>B) = \frac{B_*}{B} \qquad F(k,B) = \frac{(B_*/B)^k \exp(-B_*/B)}{k!}$$

Prompt Cusps

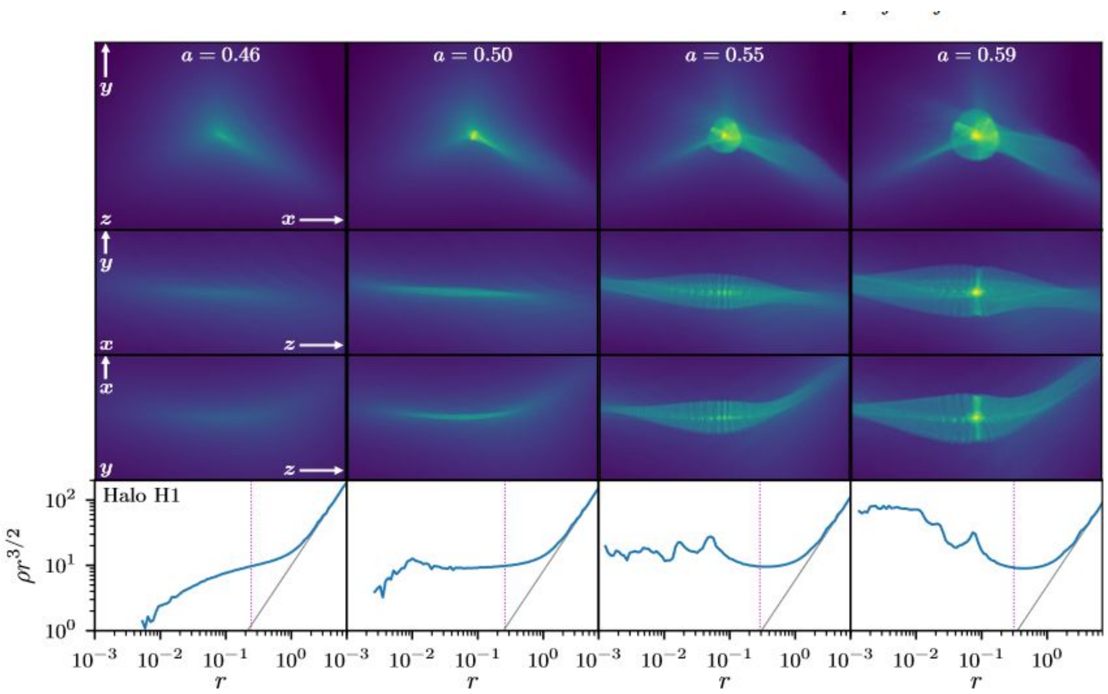
Prompt cusps are the smallest haloes in the universe. They directly form from the peaks of the (unsmoothed) density field:





1pc

Prompt Cusps

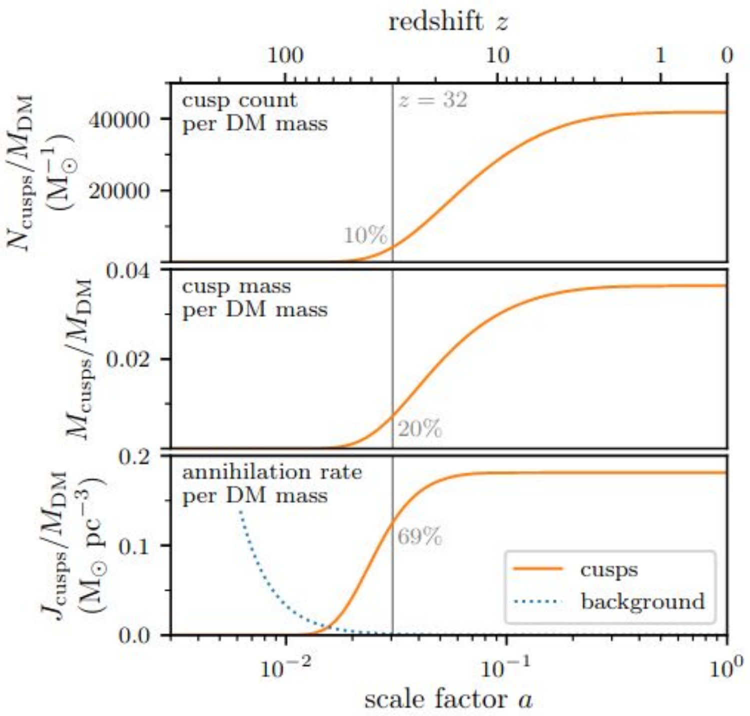


$$\rho(r) = Ar^{-3/2}$$

Delos & White (2022)

Prompt Cusps

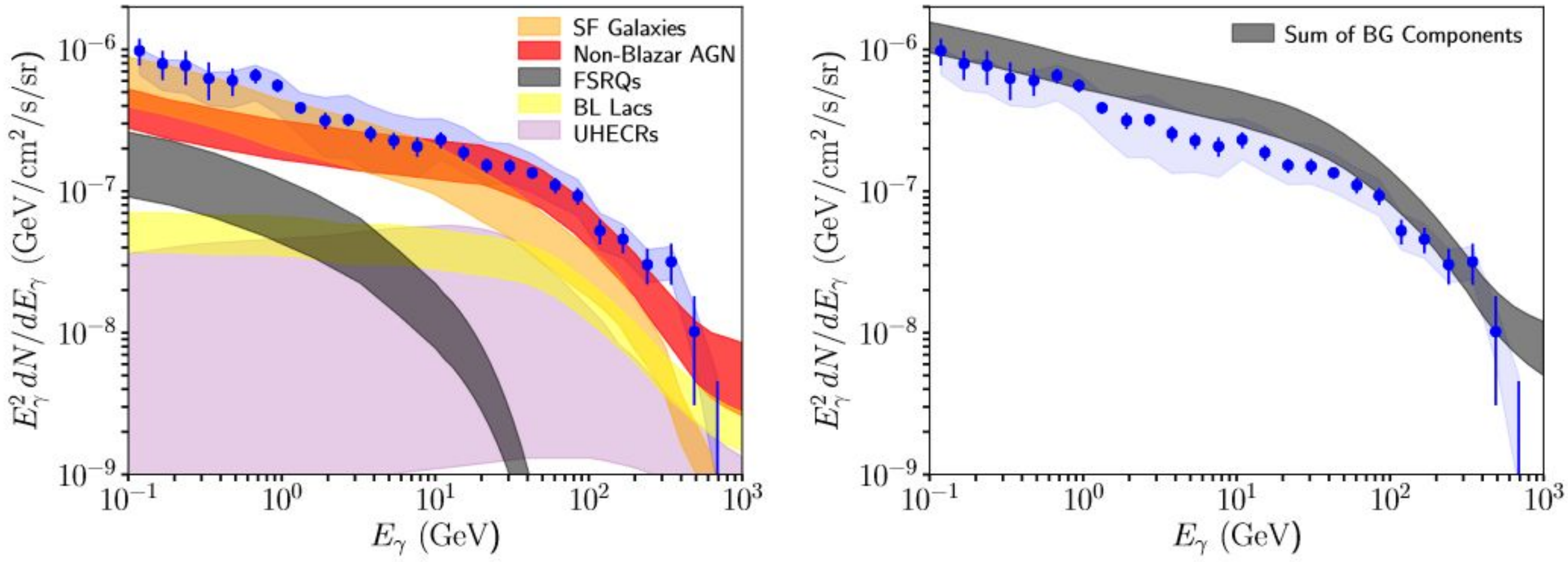
- Comoving Lag. size ~ 1pc
- Mass ~ Earth Mass
- Physical size ~ 0.01pc ~ 1000AU
- Steep density profile $\rho(r) = Ar^{-3/2}$
- There are a lot of them!
- Dominate Annihilation radiation



(Delos & White 2022)

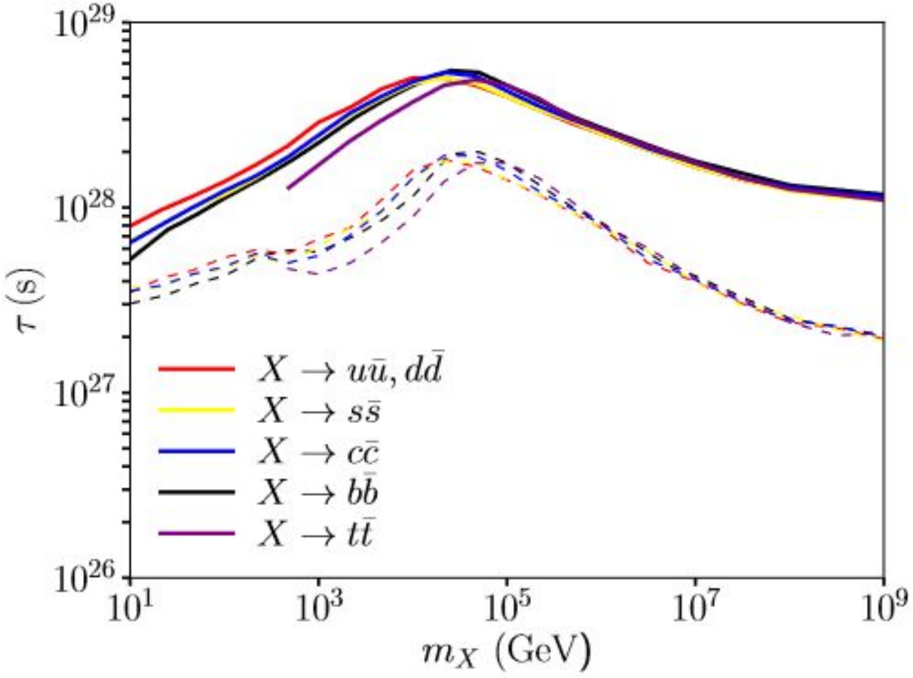
https://arxiv.org/pdf/2209.11237.pdf

The IGRB



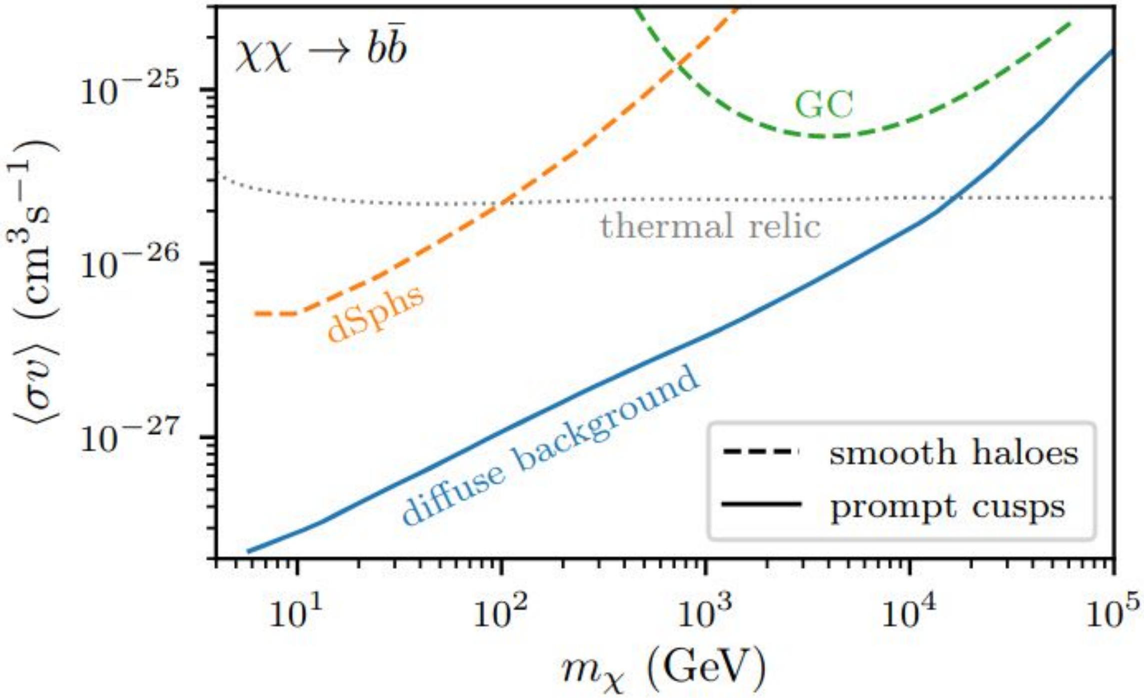
Blanco & Hooper (2018)

IGRB & DM Decay constraints



Blanco & Hooper (2018)

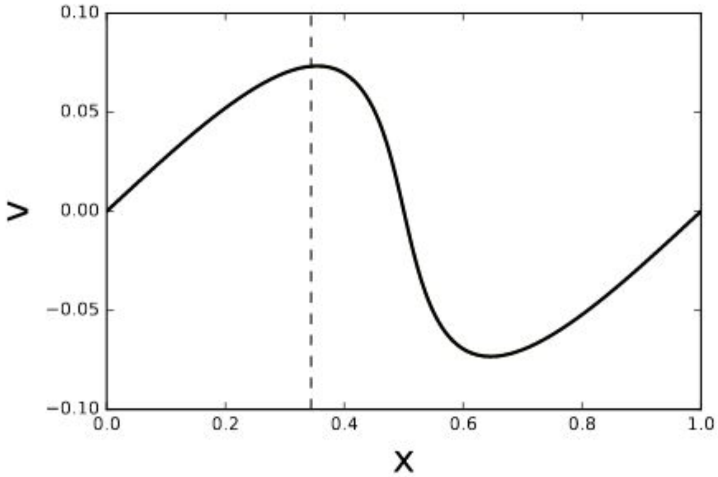
Delos & White (2022)

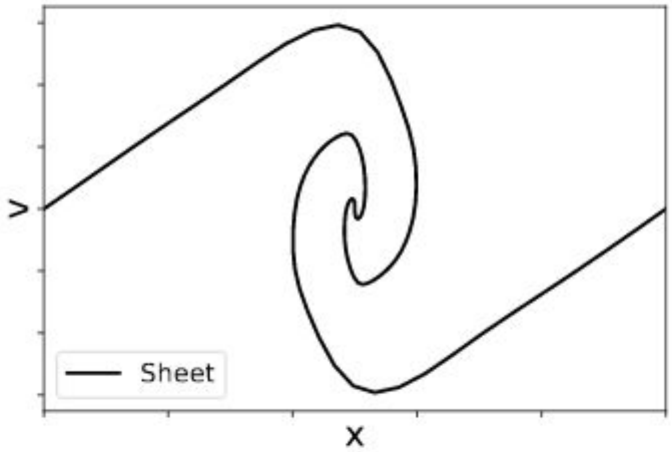


Delos & White (2022)

The primordial phase space density constraint

Perfectly **cold** dark matter

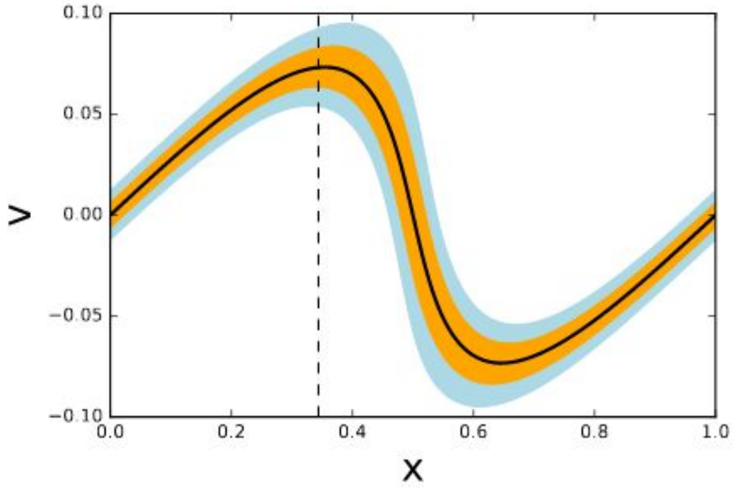


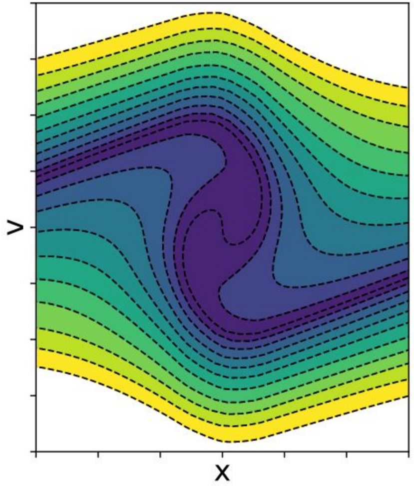


The primordial phase space density constraint

CDM has a finite thermal velocity dispersion ~ 1 cm/s. This limits gravitational collapse on some small scale.

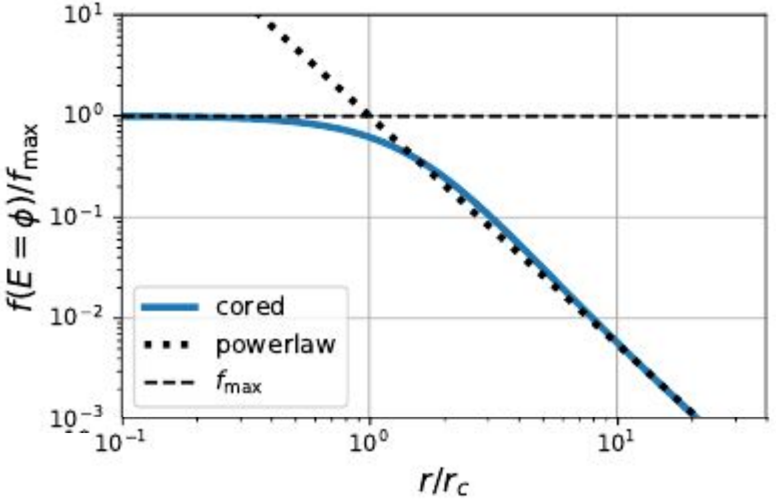
Fine-grained phase space density cannot increase



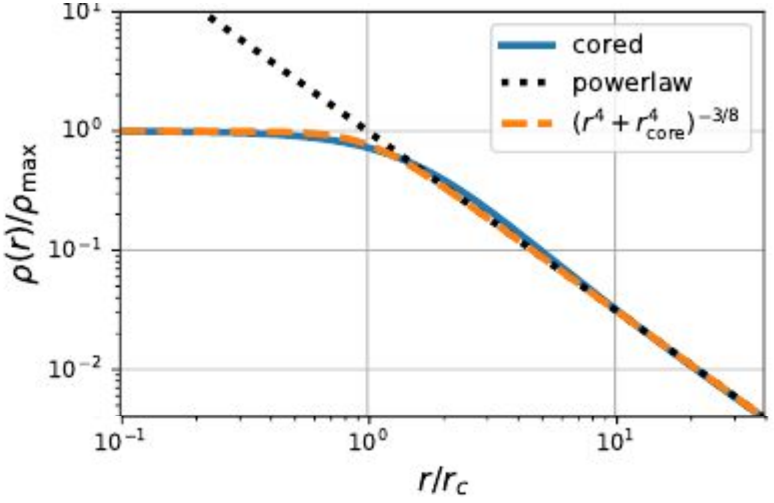


The primordial phase space density constraint

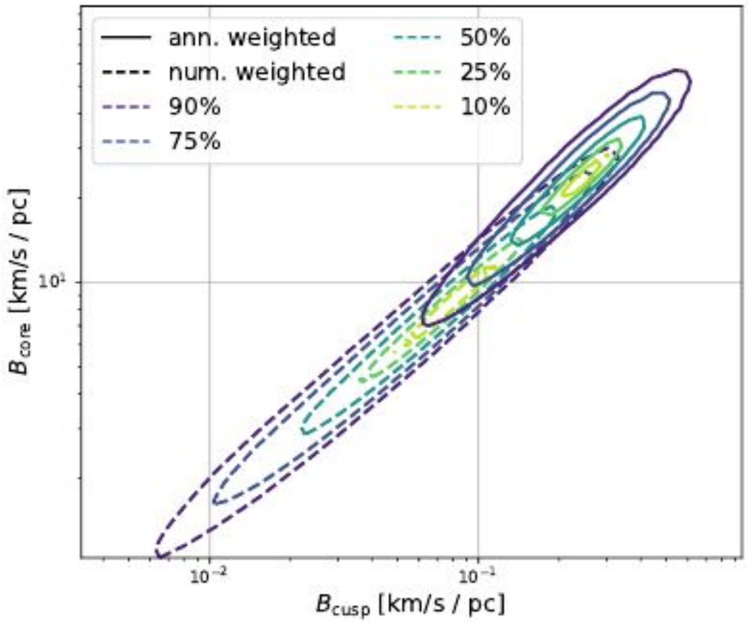
Phase space density



Density



The resilience to shocks



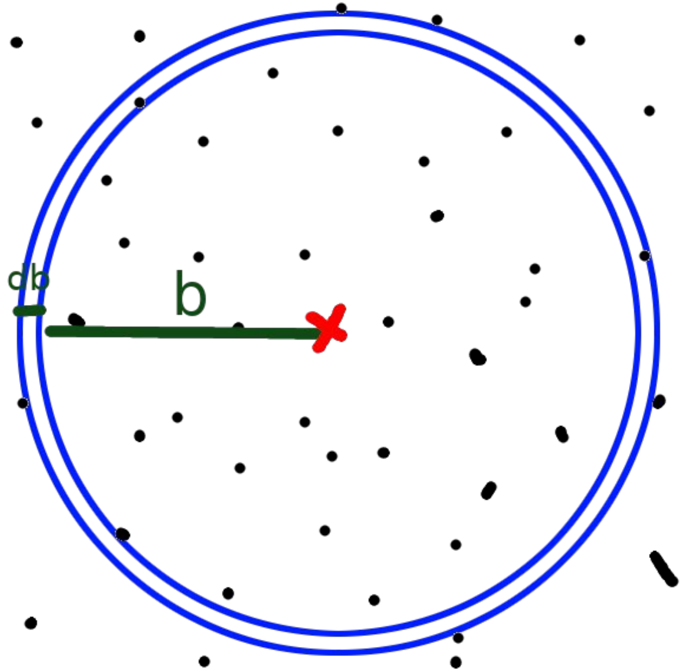
$$B_{\rm cusp} = \frac{v_{\rm circ}(r_{\rm cusp})}{r_{\rm cusp}} = \sqrt{\frac{8\pi G A}{3 r_{\rm cusp}^{3/2}}}$$

$$B_{\rm core} = \frac{v_{\rm circ}(r_{\rm core})}{r_{\rm core}} = \sqrt{\frac{8\pi G A}{3 r_{\rm core}^{3/2}}} \propto A^{2/3} f_{\rm max}^{1/3}$$

The number of encounters

A uniform stellar medium

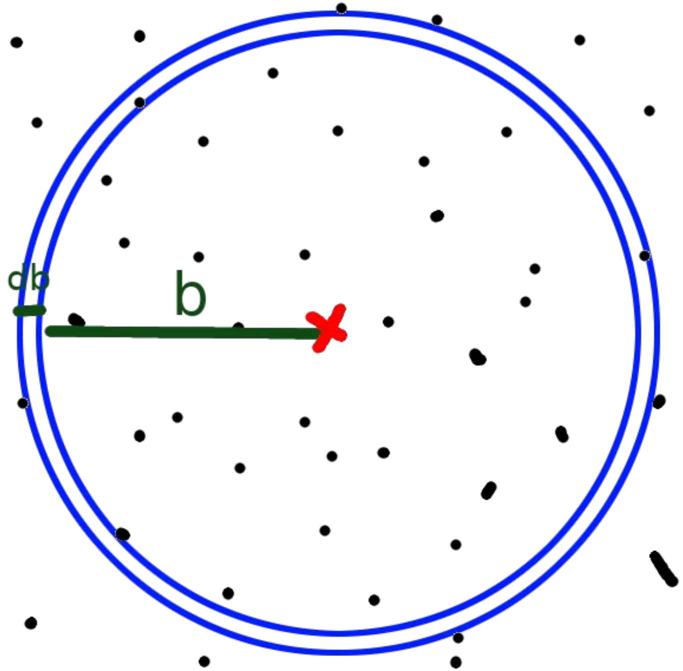
$$\mathrm{dN} = 2\pi n_* b v \, \mathrm{db} \, \mathrm{dt}$$



The number of encounters

A **uniform** stellar medium

$$dN = 2\pi n_* b v \, db \, dt$$



For an **arbitrary** stellar medium:

$$dN = (2\pi b db)(f(\boldsymbol{x}, \boldsymbol{v} - \boldsymbol{v}_{\mathbf{rel}})\Delta v^3)(vdt)(f_*(M)dM)$$

The stellar encounter conspiracy

$$\mathrm{dN} = (2\pi b \mathrm{db})(\mathrm{f}(\boldsymbol{x}, \boldsymbol{v} - \boldsymbol{v}_{\mathbf{rel}})\Delta \mathrm{v}^3)(\mathrm{vdt})(\mathrm{f}_*(\mathrm{M})\mathrm{dM})$$

$$\frac{dN}{dB} = \int_{\mathrm{6dim.}} \delta_D \left(\frac{2MG}{vb^2} - B \right) \frac{\mathrm{d^6N}}{\mathrm{d^3v\,db\,dM\,dt}} \mathrm{d^3v\,db\,dM\,dt}$$

$$= \frac{2\pi G}{B^2} \int \rho_*(\boldsymbol{x}(t))\,dt$$

Encounter Distribution

$$\chi_* = \int \rho_*(\boldsymbol{x}(t))dt$$

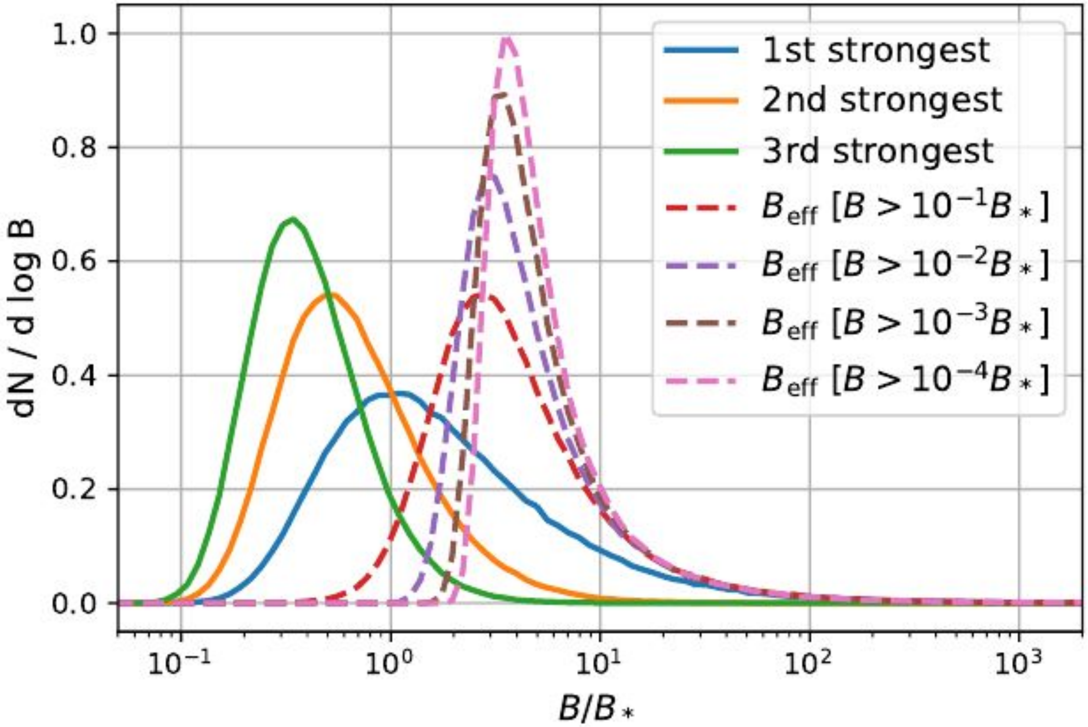
$$B_* = 2\pi G \chi_*$$

$$N(> B) = \frac{B_*}{B}$$

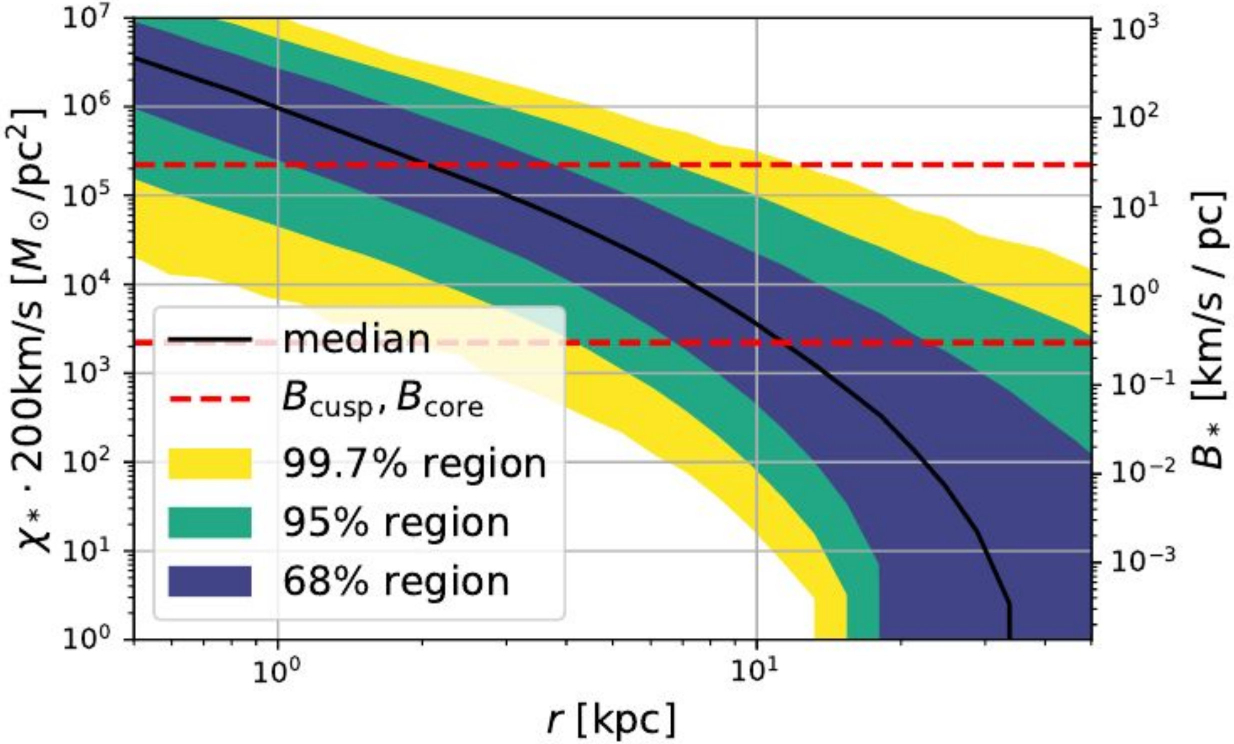
The probability of having exactly k encounters with shock parameter > B

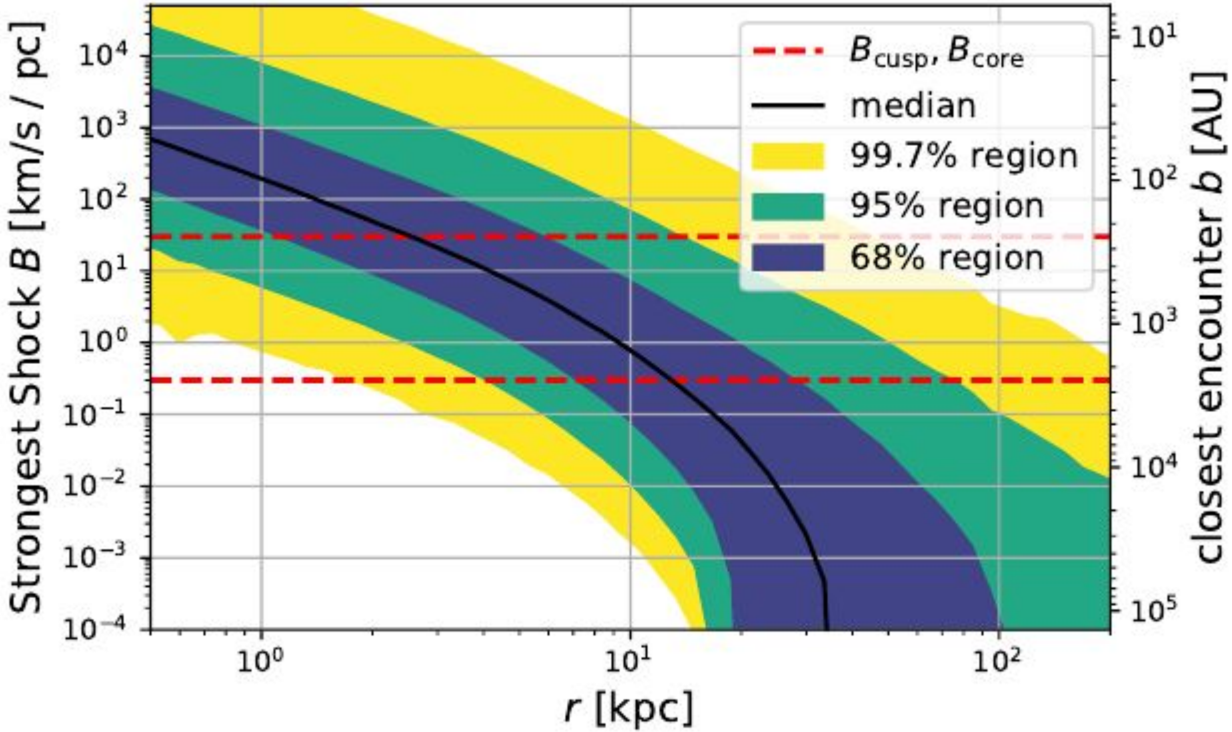
$$F(k, B) = \frac{(B_*/B)^k \exp(-B_*/B)}{k!}$$

The distribution of shocks



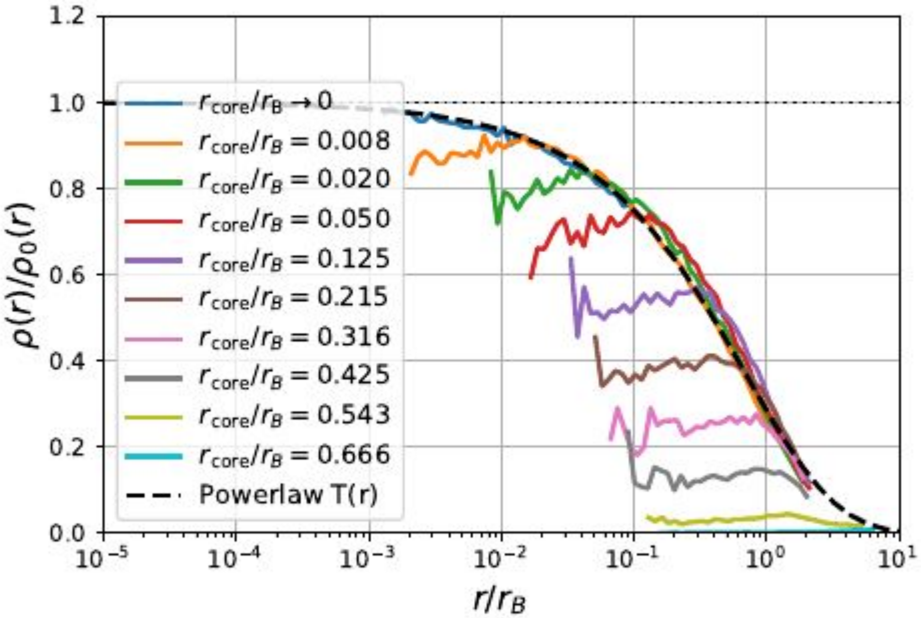
The B* distribution for orbits in the Milky Way



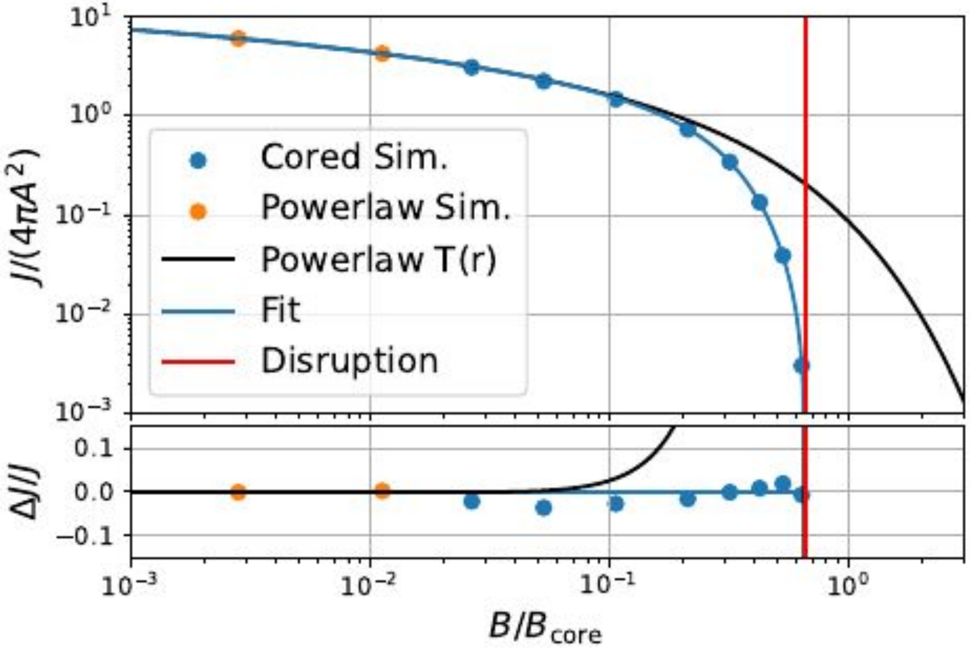


Strongest Shock B [km/s / pc]
closest encounter b [AU]
r [kpc]
$B_{\rm cusp}, B_{\rm core}$
median
99.7% region
95% region
68% region
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^0
10^1
10^2
10^1
10^2
10^3
10^4
10^5

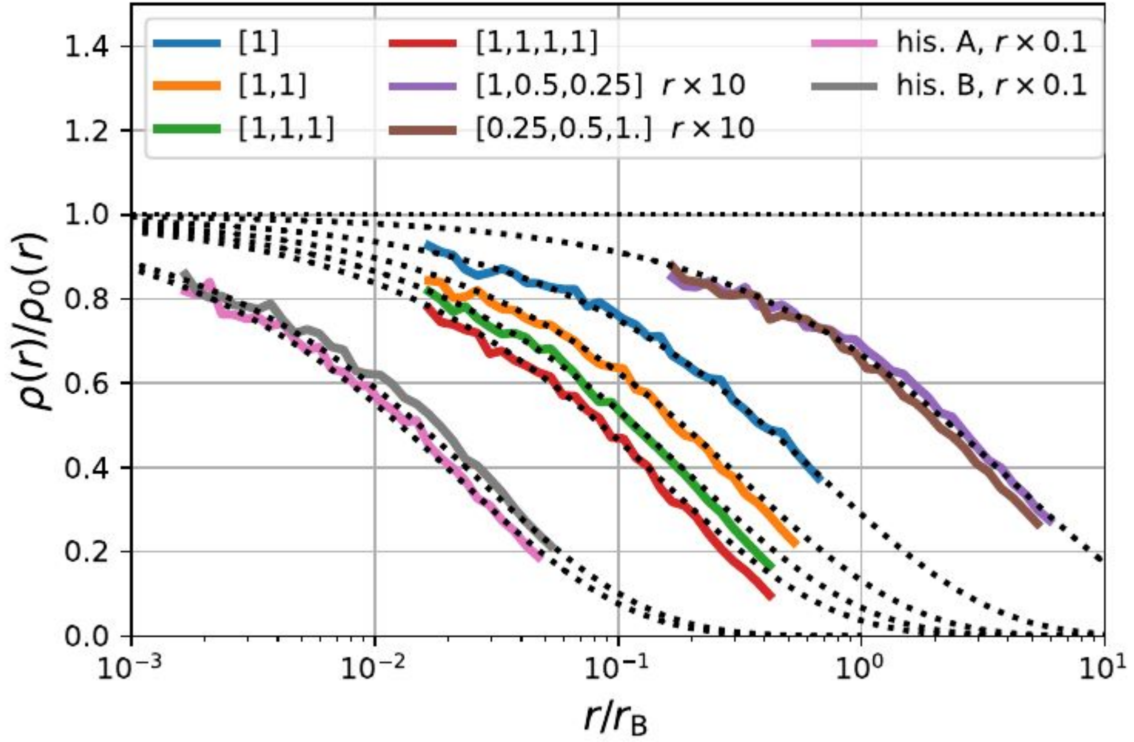
Encounters & Cored Powerlaw Profiles



Encounters & Cored Powerlaw Profiles



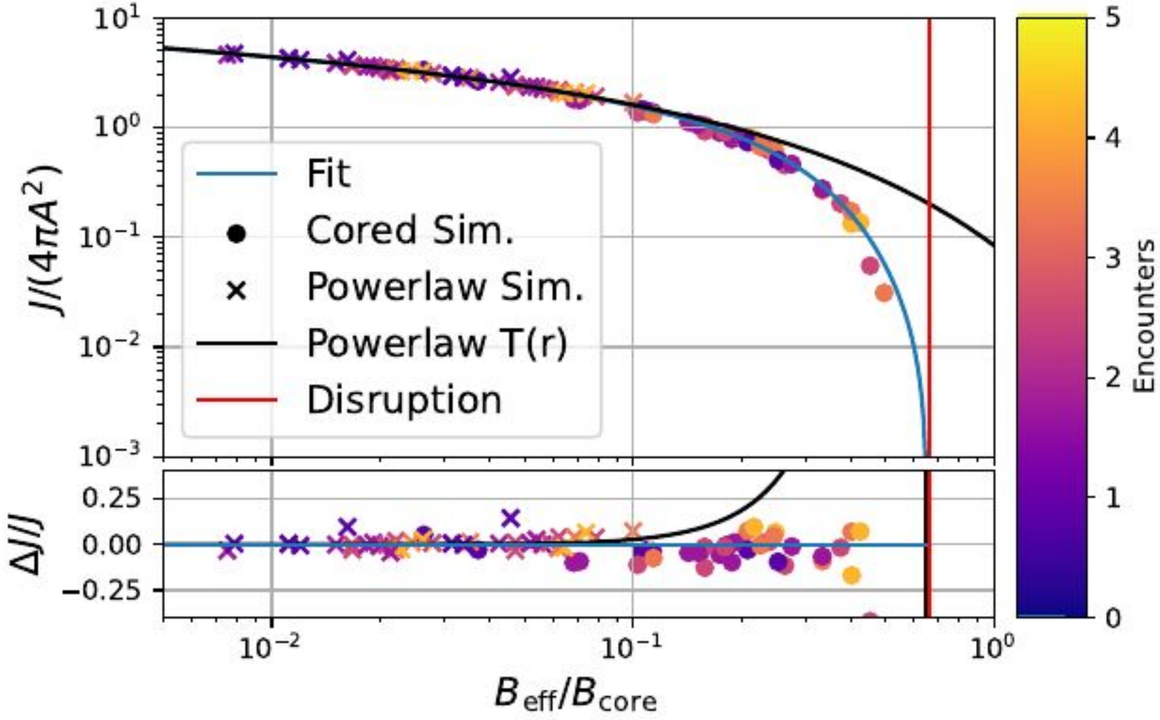
Multiple Encounters



$$B_{\mathrm{eff}} = \sqrt[p]{\sum B_i^p}$$

p = 1.2

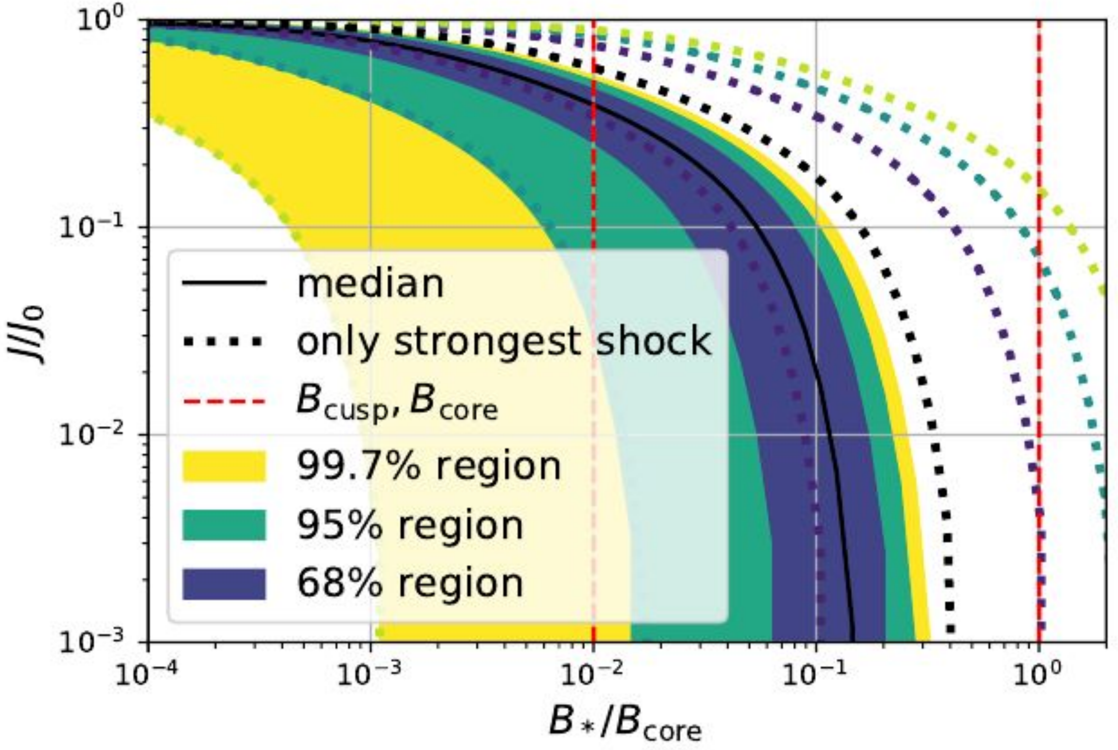
Multiple Encounters



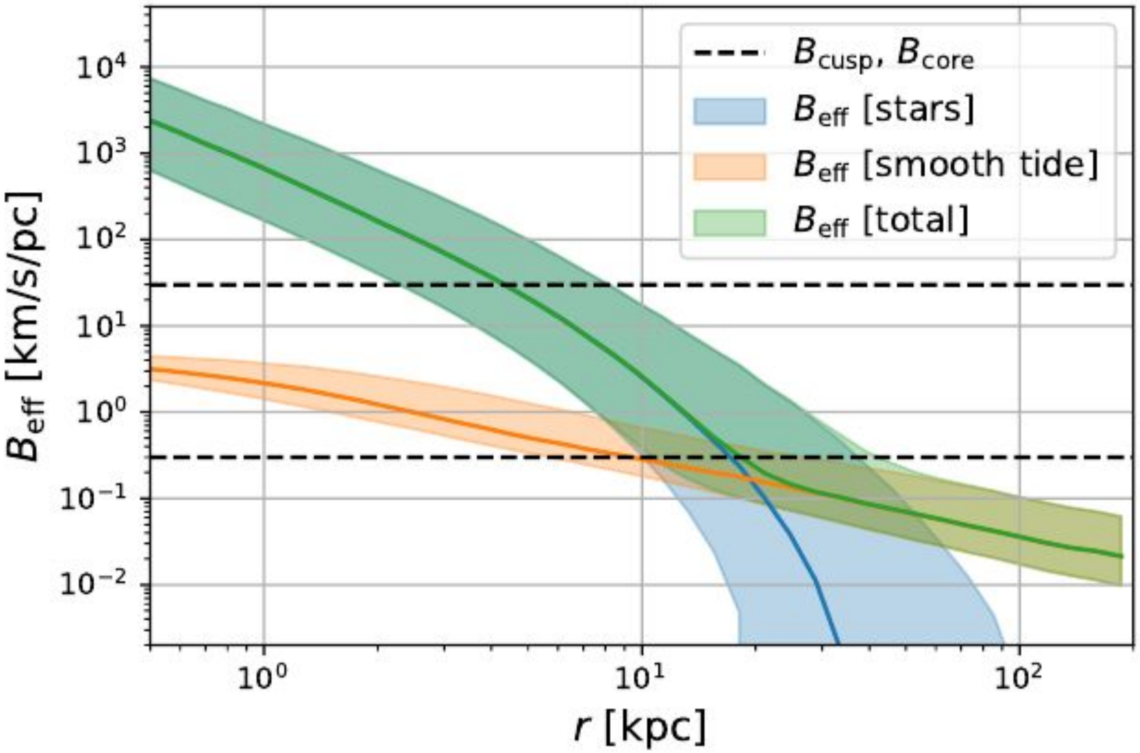
$$B_{\mathrm{eff}} = \sqrt[p]{\sum B_i^p}$$

p = 1.2

Shock histories & The annihilation Luminosity

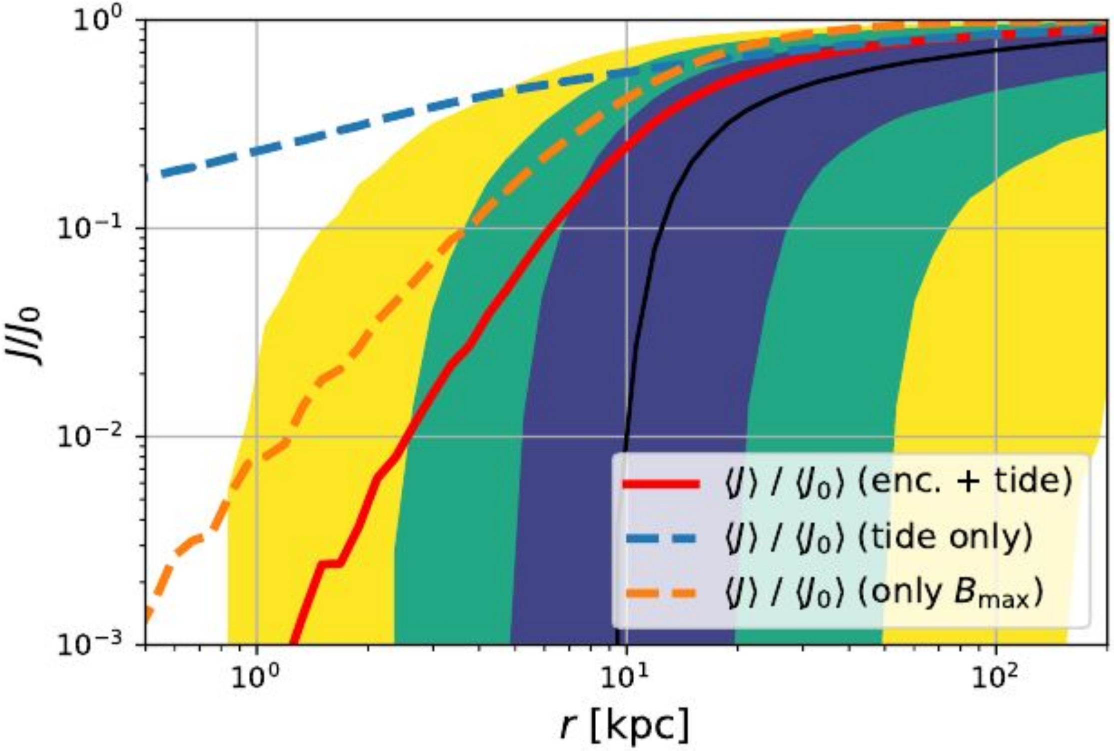


The effect of Smooth Tides



$$B_{\mathrm{eff},\lambda} = \sqrt{B^2 + 42.2\lambda}$$

Results: The reduction in Luminosity in the Milky Way



Ideas

Very **strong shocks** can form an extremely dense **caustic** with luminosity

- J/J0 ~ B/Bcusp ~ up to 10000 (only maintained for a time-period <~ year)
- However, this is unlikely to be observable